Final Report – Phase II

FEASIBILITY STUDY FOR RELIABLE MAGNETIC CONNECTION SWITCH

By: E. K. VAN DE RIET

Prepared for:

CALIFORNIA INSTITUTE OF TECHNOLOGY
JET PROPULSION LABORATORY
4800 OAK GROVE DRIVE
PASADENA, CALIFORNIA 91100

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SRI Project 5669

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ABSTRACT

The device that switches power for redundant units of a spaceborn computer must be extremely reliable. This report describes a magnetic power switch having the fail-safe characteristics that allow power to be disconnected from faulty units when failure occurs in the computer unit or in the power switch itself.

Fabrication of a breadboard model of the switch is described, as is the experimental verification of its fail-safe characteristics.

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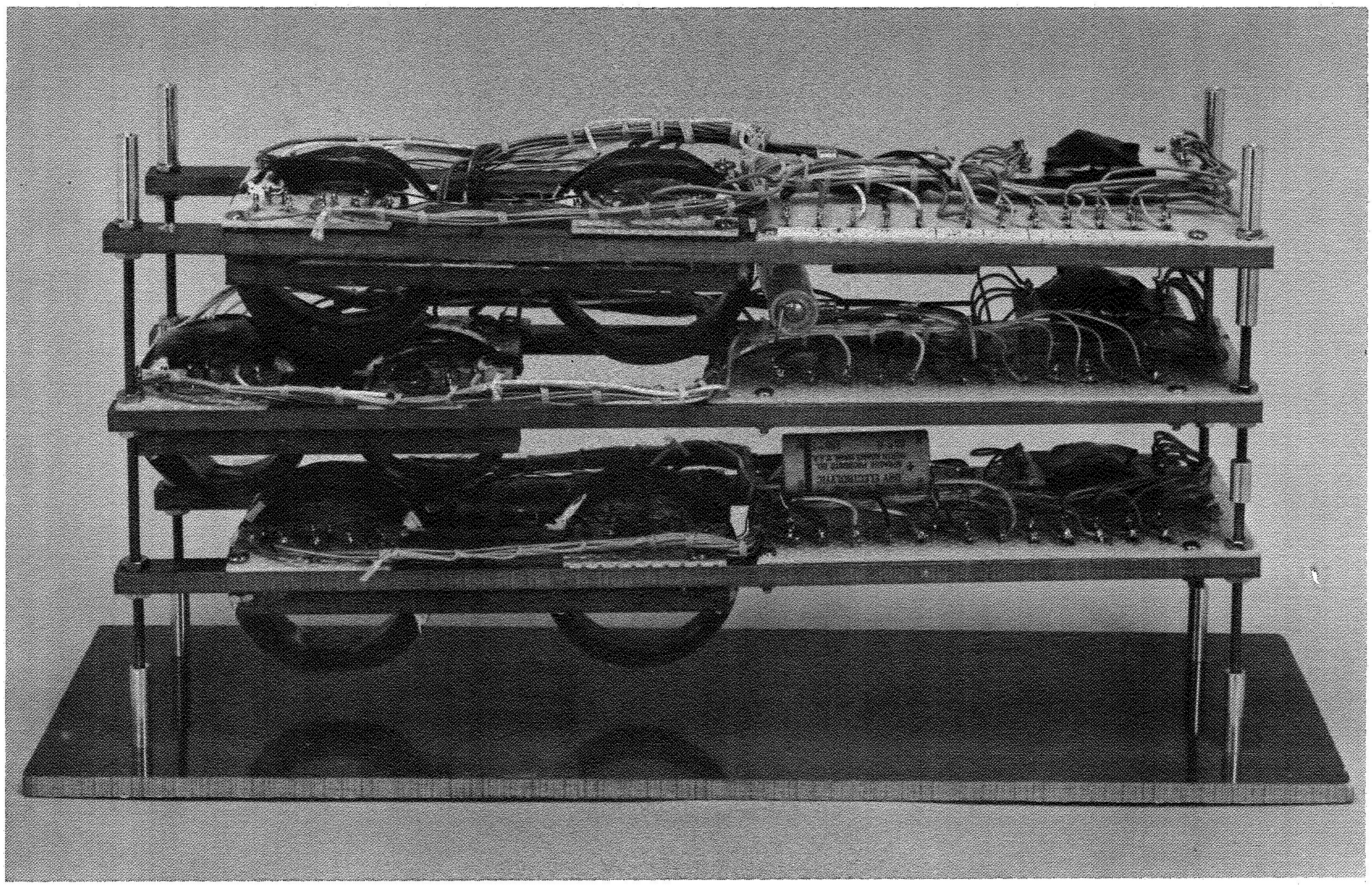

MAGNETIC SWITCHES

I INTRODUCTION

This report describes a magnetic power switch, designed to switch power to redundant units of a space-vehicle computer in the event of failure of individual units. Three breadboard switches and one failure-mode demonstration unit were fabricated. The demonstration unit has facility for showing the reaction of the switch to various types of simulated equipment failures.

A theoretical study has been made of the feasibility of a circuit designed to switch signals rather than power to the redundant units.[1]

The switches were developed for use on the Star Computer, which is being developed at Jet Propulsion Laboratories in Pasadena.[2]

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[1] E. K. Van De Riet, D. R. Bennion, and J. M. Yarborough, "Feasibility Study for Reliable Magnetic Connection Switch," Final Report - Phase I, Contract 951232 under NAS7-100, SRI Project 5669, Stanford Research Institute, Menlo Park, California (February 1966).

[2] A. Avizienis, "Design of Fault-Tolerant Computers," AFIPS, Conference Proceedings Vol. 31, Fall Joint Computer Conference, Anaheim, California, 14-16 November 1967, pp. 733-743, (Thompson Books, Washington, D.C. 1967)

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II PROJECT GOALS

The main goal of the project has been achievement of a reliable switch to control the application of power to redundant units of a spaceborn computer. The primary reliability goal is that the switch must turn off (either automatically or in response to a control signal) not only when the computer unit fails, but also when the switch itself fails. The situation to be avoided is a failure wherein a malfunctioning unit produces erroneous signals on an information bus, preventing properly functioning units from providing the correct information. Rare failures that result in the production of no signals can be tolerated, since such failures do not prevent redundant units from providing the information required from the failed unit.

More specific goals have been to fabricate breadboard models of three magnetic switches with the basic characteristics described above and to build a demonstration unit to show the effect on the switch operation caused by various types of failures. These goals have been achieved. The operation of the three switches and failure-mode demonstration unit was shown to JPL personnel. Each of the three switchs operated over a - 10°C to + 85°C temperature range switching 25 watts under control of a system of redundant voting inputs. The failure-mode demonstration unit was connected to simulate the various types of failures showing the fail-safe character of the switch.

The switches developed on this project are applicable to the power switching requirements of all the redundant units of the computer except that the control diagnosis unit has special characteristics providing the opportunity to expand the usefulness of this switching technique. It is strongly recommended that further work be done on applying the technique to these special control diagnosis unit problems.

III SWITCH DESCRIPTION

A. Power Circuit

The basic principle of the switch is described in terms of an inductor and a transformer, both of which have saturable cores. A schematic of the inductor/transformer circuit is shown in Fig. 1. To connect the load to the source, the inductor is caused to saturate and the transformer to operate in its unsaturated region. To disconnect the load from the source, the transformer is caused to saturate and the inductor is operated in its unsaturated region.

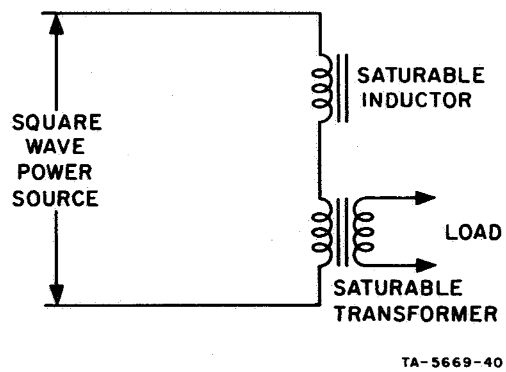

FIG. 1 INDUCTOR/TRANSFORMER CIRCUIT

In the physical realization of the switch, the inductor and transformer are incorporated in a single core with four apertures as shown in Fig. 2. The blocking and coupling apertures perform the functions of the inductor and transformer respectively: Legs 1 and 2 form the blocking aperture and Legs 4 and 5 form the coupling aperture. Leg 3 is required only to provide a path for the flux needed to saturate either of the functional apertures.

In the case described above, in which the inductor is saturated and the transformer active, Legs 1 and 2 are saturated downward and Leg 3, which has twice the flux capacity of each of the other legs, is saturated upward. Since all of the flux is accounted for in Legs 1, 2, and 3, the flux in Legs 4 and 5 must be equal and opposite, allowing flux to switch back and forth around the aperture.

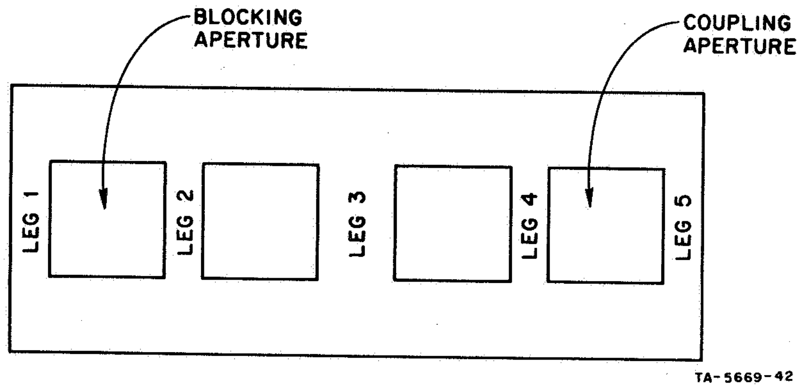

FIG. 2 CORE FOR POWER SWITCH

The windings for connecting the source and load to the core are shown in Fig. 3. The directions of the arrows on the vertical legs of the core indicate the state in which the blocking aperture is switching and the coupling aperture is not. Assume that the instantaneous source - voltage polarity is such that Line A is positive and Line B negative. Leg 1 switches downward and Leg 2 upward. Leg 4 is driven downward but, since it is already saturated in this direction, cannot switch. Leg 5 is driven in the set (upward) direction but cannot switch because there is no path for the flux except through the source leg. Flux cannot switch through the source leg because it is held saturated in the upward direction with a bias magnetomotive force (MMF). An additional factor that helps prevent Leg 5 from switching is that the long flux path through Leg 3 requires more MMF to switch. Since no switching occurs in either Legs 4 or 5 of the coupling aperture, no voltage is induced in the load windings, effectively disconnecting the load from the source.

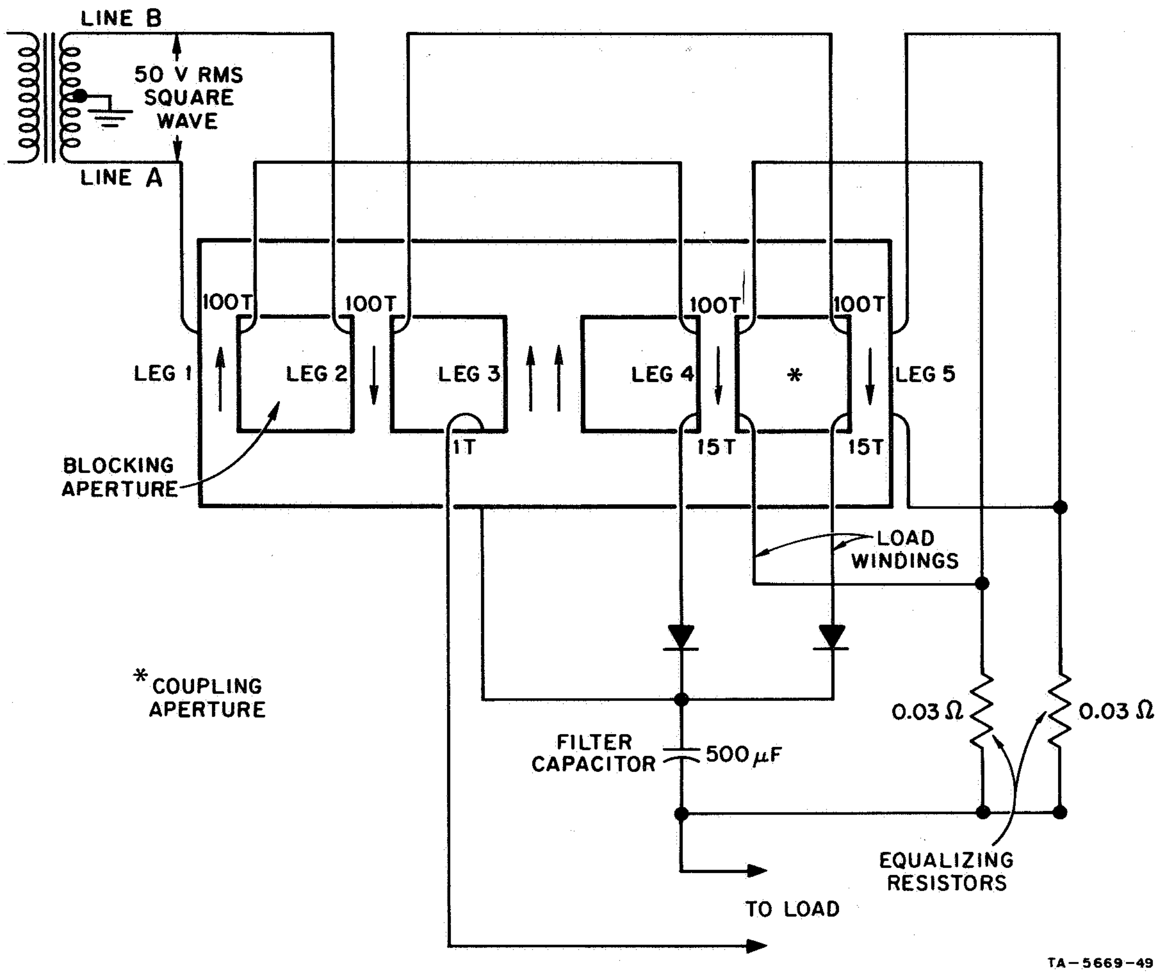

FIG. 3 POWER CIRCUIT

To connect the load to the source (the on case), Legs 1 and 2 are saturated downward, Leg 3 upward (as for the off case), and Legs 4 and 5 opposite from each other. By the same argument used in the off case, Legs 4 and 5 switch and Legs 1 and 2 do not. The switching of Legs 4 and 5 induces voltage in the load windings, effectively connecting the load to the power source.

The equalizing resistors shown in Fig. 3 are explained in Sec. IV-F.

B. Control Circuit

To change the position of the switch, a MMF must be applied so as to saturate the active aperture or unsaturate the inactive aperture.

It is more practical to choose the first approach of driving magnetic paths into saturation rather than out because overdriving into saturation produces no ill effects. Conversely, a precise amount of MMF is required to drive a core out of saturation, since any significant overdrive causes the path to go into saturation in the opposite direction.

To turn the breadboard model switch off, Legs 4 and 5 (Fig. 3) are driven in the downward direction. Since Leg 3 is always saturated in the upward direction, the flux in Leg 3 balances out the flux in Legs 4 and 5, leaving Legs 1 and 2 (the coupling aperture) in the unsaturated state. To turn the switch on, Legs 1 and 2 are driven in the downward direction.

C. Voter Circuit

The switch is required to operate in response to multiple input signals such that any two or more out of five inputs will cause the switch to turn on; a single input will neither cause the switch to turn on nor hold it on. The input signals are continuous dc currents applied to the voter windings shown in Fig. 4. It is required that these windings pass through the aperture between Legs 2 and 3; however, they may return following any path around the outside of the core so long as they do not pass through any apertures. The physical structure and mounting members of the core make it convenient to return the windings around the outside of Leg 1.

A bias MMF applied downward on Legs 4 and 5 is required to prevent any single input signal from turning the switch on. The threshold characteristics of the core tend to help achieve the non-linearity required to give the switch the full- on or full- off character desired in any switch. The core switching threshold by itself, however, is much too small to hold the switch on with the MMF magnitudes reached in a switch of this type. A positive feedback winding from the output to the input produces a good on-off ratio and near snap-action type of operation. This feedback is accomplished simply by passing the lead carrying current to the load once through the aperture between Legs 2 and 3 in the direction that tends to saturate Legs 1 and 2 in the

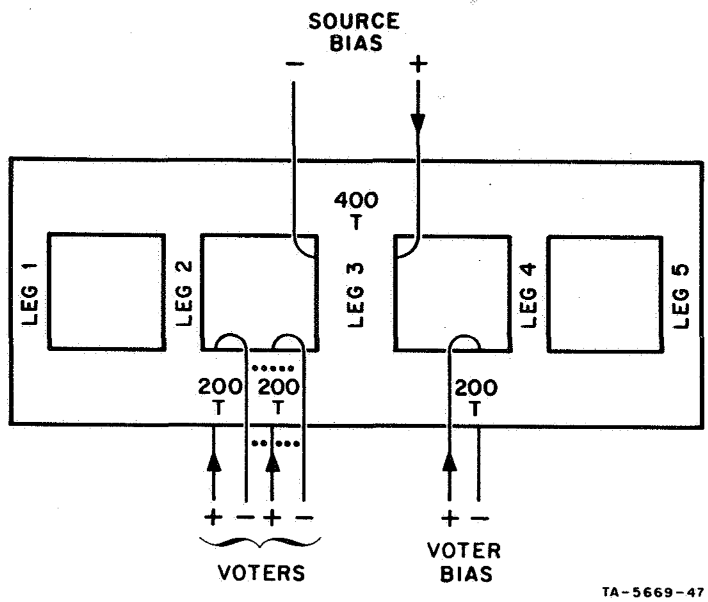

FIG. 4 SIGNAL AND BIAS WINDINGS

downward direction as shown in Fig. 3. A holding MMF on Leg 3 in the upward direction is required during the on state of the switch. (In practice, this MMF is left on during the off state for convenience, but is not required.) The holding MMF is accomplished by applying equal MMF's in the downward direction on Legs 1, 2, 4, and 5.

Summarizing, assume that the switch is in the off state and a single input signal appears, applying an MMF downward on Legs 1 and 2. In order to saturate Legs 1 and 2, flux must switch downward through Legs 1 and 2 and upward in Legs 4 and 5. Flux cannot switch in Leg 3, since it is saturated upward. Since Legs 4 and 5 have a downward bias of a magnitude roughly equal to the input MMF, flux does not reverse and the switch stays off. When a second input signal appears, however, sufficient MMF is applied to overcome the bias on Legs 4 and 5. Legs 1 and 2 saturate downward and Legs 4 and 5 switch into the active region. Current begins to flow through the feedback winding into the load, driving Legs 1 and 2 firmly into saturation. This feedback is not of sufficient magnitude, however, to hold the switch should one of the input signals be removed. Additional input signals beyond two have no significant effect, since they drive Legs 1 and 2 further into saturation.

IV SWITCH DESIGN

A. Introduction

Four- and five-aperture cores were used in developing the switch. The four-aperture core is shown in Fig. 2. The five-aperture core is similar, except that Leg 3 is made up of two separate legs, each with half the flux capacity of Leg 3 of the four-aperture core. Since these two legs are treated as one and are always held saturated in the set direction, there is no significant difference in the operation of the four- and five-aperture cores. For the sake of simplicity, only the four-aperture core is discussed in this report.

B. Core

1. Material

The material for the laminations of the cores is Orthonal (50 percent Nickel; 50 percent Iron) of a thickness of 0.002 inch. High flux density and good saturation are the two main material characteristics desired. Laminations must be thin enough to reduce eddy current effects to a tolerable level at 2.4 kHz. The threshold characteristics are not crucial in this application, because MMF's involved in these power levels are large compared to the threshold of the longest flux path in the core.

Metal rather than ferrite is used in this application because it can be obtained with better saturation characteristics and higher saturation flux density. However, the switch can be designed around any square-loop magnetic material with reasonably high flux density and good saturation characteristics.

2. Shape

The basic shape requirement of the core is two apertures connected by a flux closure path, as shown in Fig. 2. The angularity of the core is critical only insofar as it affects saturation characteristics. The core is designed so that the legs of the core are all at right angles to each other; the flux paths are thus either parallel or at right angles to the preferred direction of magnetization of the metal. Present notions of domain wall behavior indicate that better saturation characteristics are obtained with square rather than rounded corners. This has been neither verified nor contradicted in the laboratory with the cores used in this switch.

The cross-sectional areas of all the vertical legs of the core are equal except for Leg 3, which is twice the others. The cross-sectional area of the horizontal legs are equal to Leg 3. The vertical leg cross-sectional area is a function of the flux density of the material, the number of primary winding turns, and the driving voltage amplitude and frequency; specifically:

$$A = \frac{V}{4BFT} \tag{1}$$

where

A = Cross sectional area of a vertical leg in cm^2,

V = Amplitude of the drive voltage square wave in volts,

B = Saturation flux density of the core material in volt-microseconds/cm^2,

F = Frequency of the drive voltage (square-wave) in Hz, and

T = Number of primary winding turns.

The amplitude of the drive voltage square wave is specified and the flux density of the material is chosen to be as large as possible; however, the cross-sectional area of the core leg and the number of primary turns can be chosen arbitrarily, so long as their product is equal to the value required by the equation. The selection of a cross-sectional area and number of primary turns is calculated on the basis of minimum volume (and, therefore, approximately minimum weight) of the core plus its windings. (This calculation is explained in Appendix A.) Leakage flux is another factor that would limit the cross-sectional area of the core if the minimum volume calculation indicated many turns on a core of small cross section. The present core size and shape is well within the range where leakage flux is not significant relative to the elastic flux of the material.

The various leg lengths of the core should, in general, be as short as possible so as to reduce both power loss and overall weight and volume. The actual lengths used result from the minimum volume calculations mentioned above. Very long or very short paths might result in trouble with poor saturation characteristics and excessive leakage flux; however, the present core is well within the range where these problems are not encountered.

The precision of the dimensions of the core are crucial only in that the cross-sectional area of the vertical legs (Legs 1, 2, 4, and 5 of Fig. 2) are equal to each other and equal to half the cross sectional area of the source leg (Leg 3) and the horizontal legs. It is practical to hold tolerances of 0.001 inch in etching the core laminations; this level of precision is adequate to cores of this general size and shape. It is impossible to put an exact specification on the maximum allowable variation of dimensions, since the result of variation is a gradual deterioration of performance in terms of on/off ratio of the output voltage and efficiency. The recommended core dimensions for various power outputs are given in Table I.

The core cross section could be made round by progressively varying the leg widths of the laminations. The advantage of having round-cross-section vertical legs is to allow more efficient use of aperture space in the case where the rotating-bobbin winding technique (described in Appendix B) is desired for the power windings. The disadvantages of this technique are that the structure is less compact (because the horizontal legs are wider than for the rectangular cross section case) and the cost of fabrication is greater.

It is not clear whether an overall volume advantage would be gained from going to round cross sections. Probably the decrease if any would be too small to warrant the added cost. Further investigation is required to obtain a definite answer to this question.

3. Fabrication

The cores used in these switches were fabricated by Magnetics Incorporated, Butler, Pennsylvania. A photograph of a core is shown in Fig. 5. The photoetching process is standard practice, requiring only the usual care and attention. The stacking, insulating, and annealing proficiency may vary from manufacturer to manufacturer since they have not reached the level of standardization of the photoetching process. Specific detailed instructions for mounting and winding the cores are given in Appendix B.

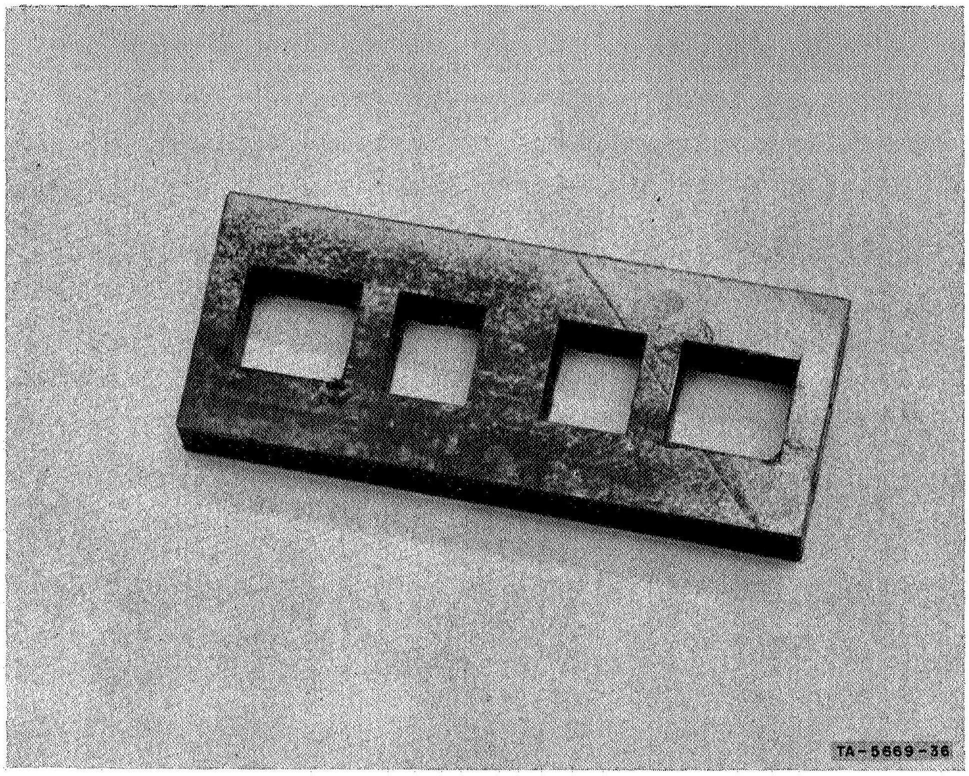

FIG. 5 PHOTOGRAPH OF FOUR-APERTURE CORE

C. Windings

The number of primary winding turns are calculated on the basis of Eq. (1). These calculations are described in Appendix A. The secondary turns are calculated on the basis of the turns ratio to give the desired voltage output, taking into account the rectifier drop and regulator drop (if necessary). A primary/secondary ratio of 100:15 was used in the switches developed on this project.

The minimum allowable wire size is determined by the temperature rise and power loss that can be tolerated in the winding. While calculation of the power loss is trivial, the temperature rise calculation is so difficult as to be impractical. The difficulty arises from the basic complications of three-dimensional heat-transfer problems in addition to the wide variations due to the core mounting technique and the environment in which the switch ultimately will operate. Published data on wire sizes for various transformer configurations are useless, because the core in this switch can dissipate heat so much more effectively than is the case in normal transformer applications. Laboratory experiments showed a 5°C rise in temperature under conditions of wire size and current for which a 30°C rise in temperature was indicated by the published data.

The only significant reason to attempt to approach the minimum allowable wire size is to reduce the weight and volume of the switch. All other aspects of the switch, such as efficiency and regulation, are improved by making the wire larger.

The experimental approach is recommended for finding the minimum wire size for a given power output. A curve of temperature as a function of power output for a given sample switch can be measured and extrapolations made from the curve.

Winding placement, insulation between layers, and other considerations of this type are not crucial to the operation of the circuit. Decisions regarding these factors should be made on the basis of reducing the probability of failure.

The design of the control windings (shown in Fig. 4) depends upon the required control MMF, the desired resistance to allow for voltage drive, and the minimum safe wire size. Winding resistance is important, since it controls the current. Fail-safe requirements dictate that the control winding be driven from a voltage source. It is also important that very little series resistance be added. These requirements are explained in greater detail in Sec. V.

The control MMF's are not critical in magnitude; however, the ratio of the voter bias MMF to the voter MMF (called the voter ratio) has tolerance limits, which depend upon the magnitude of these MMF's. The control MMF's used in the switches developed here were of sufficient magnitude to give a tolerance on the voter ratio of about ± 5 percent. The design value of the control MMF's given in Table II is obtained from experimental results. After a switch is designed and fabricated, the design values of the control MMF's are tested and then adjusted. The voter ratio range is tested (as explained in Part D, below) and adjusted to mid-range. If the range is inadequate, the magnitude of the design value is increased as far as necessary to obtain the desired range. The expression from which the control winding turns and wire sizes are calculated is:

$$\text{MMF} = \frac{V}{R_T T} \times T \tag{2}$$

$$= \frac{V}{R_T} \tag{3}$$

where

MMF = the required control MMF,

V = the source voltage,

R_T = the resistance per turn, and

T = the number of turns.

The turns cancel in Eq. (3), leaving just the voltage divided by the resistance per turn. The resistance per turn is calculated for a given source voltage and required MMF. The length of a turn is determined from the size of the bobbin. Then the resistance per unit length and finally the wire size are calculated. The turns are set at a value where the current-carrying capacity of the wire is adequate. The turns can be increased further, if desired, to lower the current to a level compatible with the desired type of drive circuit.

D. Recommended Designs

Recommended designs are given in Table I for 5-, 10-, 20-, and 40-watt switches. Information that is independent of the power output of the switch is given in Table II.

The reference dimension of the core is the width of a vertical leg of an aperture. All other dimensions are obtained by multiplying the reference dimension by the appropriate factor, as shown in Fig. 6. The length, width, and reference dimension of the core for each power output are given in Table I.

The efficiency of the core and its windings is about 95 percent for all of the switches, but the loss in efficiency (20 percent) due to the rectifiers is high, as in any case where rectification at low voltage is necessary. The designs given in the table allow $\approx$ 1V for insertion of a regulator circuit. If the square-wave power source is well enough regulated, and the variation of load on the switches is held to roughly 50 percent, regulators would not be needed.

Load variation must be taken into account in determining the optimum voter ratio (ratio of voter bias MMF to voter MMF). The voter ratio can tolerate quite large variations in load. The load on the switch will vary, due to the normal operation of the computer unit being driven. From the point of view of control circuit design, the range of power output levels given in Table I may also be considered load variation. Another type of load variation is the increase in load impedance looking into the computer unit being driven, when the voltage is reduced to the off level. The off voltage for this application is about 0.5V. The characteristics of the switch are such that the off voltage tends to be higher as this impedance increases. The optimum value of the voter ratio depends upon all three of these types of load variations. Measurements on the switches showed that when the voter ratio was adjusted to its optimum value, a load range of 1 to 15 Ω could be tolerated in both the on and off states of the switch, still leaving a 5 percent tolerance on the ratio. The design value ratio of 1.33 in Table II is given as a starting point from which to adjust the

Table I

DESIGN RECOMMENDATIONS

Parameter	Value for Capacity of 5 Watts	10 Watts	20 Watts	40 Watts
Core Length (inches)	2.57	3.05	3.63	4.32
Core Width (inches)	0.976	1.16	1.38	1.64
Core Dimension x (inch)	0.134	0.159	0.189	0.225
Primary Turns (each leg)	224	158	112	79
Primary Wire Gauge	31	28	25	22
Secondary Turns (each leg)	34	24	17	12
Secondary Wire Gauge	25	22	19	16
Feedback Wire Gauge	25	22	19	16
Balance Resistance (ohms)	0.05	0.04	0.03	0.03
Primary Current "on" (amperes)	0.156	0.310	0.617	1.23
Secondary Current "on" (amperes)	1	2	4	8
Primary Current "off" (ampere)	0.006	0.010	0.017	0.029
Power Loss in Winding (watt)	0.200	0.332	0.560	0.930
Power Loss in Core (watts)	0.3	0.5	0.85	1.45
Power Loss in Core Plus Windings (watts)	0.5	0.832	1.41	2.38
Efficiency of Core and Windings (%)	93.6	94.6	95.3	96.1
Efficiency Including Rectifier (%)	77	76.5	76	75
Equivalent Series Resistance Referred to Secondary (ohms)	0.164	0.087	0.053	0.04

Table II

GENERAL DESIGN INFORMATION

Parameter	Value
Turns ratio, secondary to primary	15:100
Wire insulation	Heavy Nyleeze or equivalent
Feedback winding turns	1
Voter Ratio	1.33
Voter MMF	9 ampere-turns
Voter bias MMF	12 ampere-turns
Source bias	Greater than 28/ampere-turns

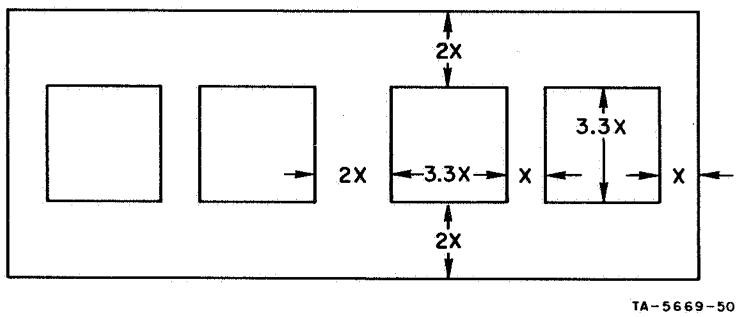

FIG. 6 CORE DIMENSION FACTORS

ratio to its optimum value for the particular power output level, for which it is designed, and for the particular load variation to which it will be subjected.

The voter ratio is tested by connecting the design value voter-bias MMF to the core with the power connected to the power windings and the design value load connected to the output. A variable MMF then applied to the voter-winding leg of the core is increased until the core turns on, then decreased until it turns off. The lower limit of the voter MMF is half the turn-on MMF; the upper limit is equal to the turn-off MMF. The test must be repeated for the maximum value to which the load resistance will rise when the switch is turned off. The voter range can be increased by increasing the voter bias MMF. This range need not be large, because the voter and voter-bias windings will be driven from the same voltage source. Thus, variation in the supply voltage will vary voter and voter bias MMF's together, keeping the ratio the same. The accuracy of the ratio of the MMF's depend only on the accuracy of the ratio of the resistances of the windings and their tracking with temperature. A 5 to 10 percent tolerance in the voter ratio is adequate.

After the voter and voter bias MMF's are obtained from the above tests, the wire size and number of turns are determined, as explained in Part C. If the required wire sizes are too small for convenient windings, a series resistor can be used, providing that it is common to all of the voter windings and to the voter bias winding, so that the same voltage appears across them all even though it changes as the number of voter inputs change. The resistances of the voter windings, voter bias winding, and series resistor must be such that when two voters are on, the design value MMF's are applied to the proper legs. When more voters are turned on, the MMF in each winding will decrease, due to the increased drop across the series resistor, but the net MMF holding the core on will increase.

The inconveniences of voltage drive are well worth tolerating in order to gain the reliability advantages explained in Sec. V.

E. External Circuit

The operation of this switch is affected very strongly by the flux or volt-microsecond balance between the two halves of the square-wave voltage source.

Flux switching in a leg of a core is cumulative, in that the amount of flux switched in one direction during one half of the cycle must be equal to the flux switched in the opposite direction during the other half cycle. If the flux switched in both directions is not equal, the flux level for the half cycle in which more flux is switched increases until saturation is reached. Once saturation is reached, the core stops switching and no longer generates a back voltage, thereby causing the input current to rise rapidly.

In order to meet the requirement of equal flux switching in both directions, the driving square-wave source must have equal voltage-time products under the two halves of the square-wave drive. This equality is ensured by using a transformer drive, since the transformer itself has the same flux-switching balance requirement. This flux balance is referred to herein as directional balance. For directional balance, only the net flux change per half cycle must be balanced.

Another condition of balance that must be maintained is that equal and opposite flux must switch in the two legs of a given aperture. Not only must the net flux change in the two legs be equal for any half cycle, but the rate of change of flux in the two legs at any instant must also be equal.

The output aperture with its primary and secondary windings is shown in Fig. 7. The common 0.03 Ω resistor is omitted in order to facilitate the explanation. Assume that the voltage on Leg 5 primary is positive as shown at point A in the waveform on the figure. Current flows in the secondary on Leg 5 but not Leg 4 because the diode is cut off. The load current in the secondary produces a corresponding current in the primary winding. The current in the primary causes a voltage drop across the resistance of the winding, reducing the effective voltage that produces the flux change in the core. The rate of change of flux in Leg 4 is greater than that in Leg 5 because no decrease in voltage corresponding to that in Leg 5 has occurred; this is because the secondary winding on Leg 4 is not drawing current. These conditions violate the requirement of equal rates of change of flux in the two legs: The primary winding on Leg 4 is trying to change flux in Leg 4 at a greater rate than it is changing in Leg 5. The net result of this condition is that current rises in the primary of Leg 4.

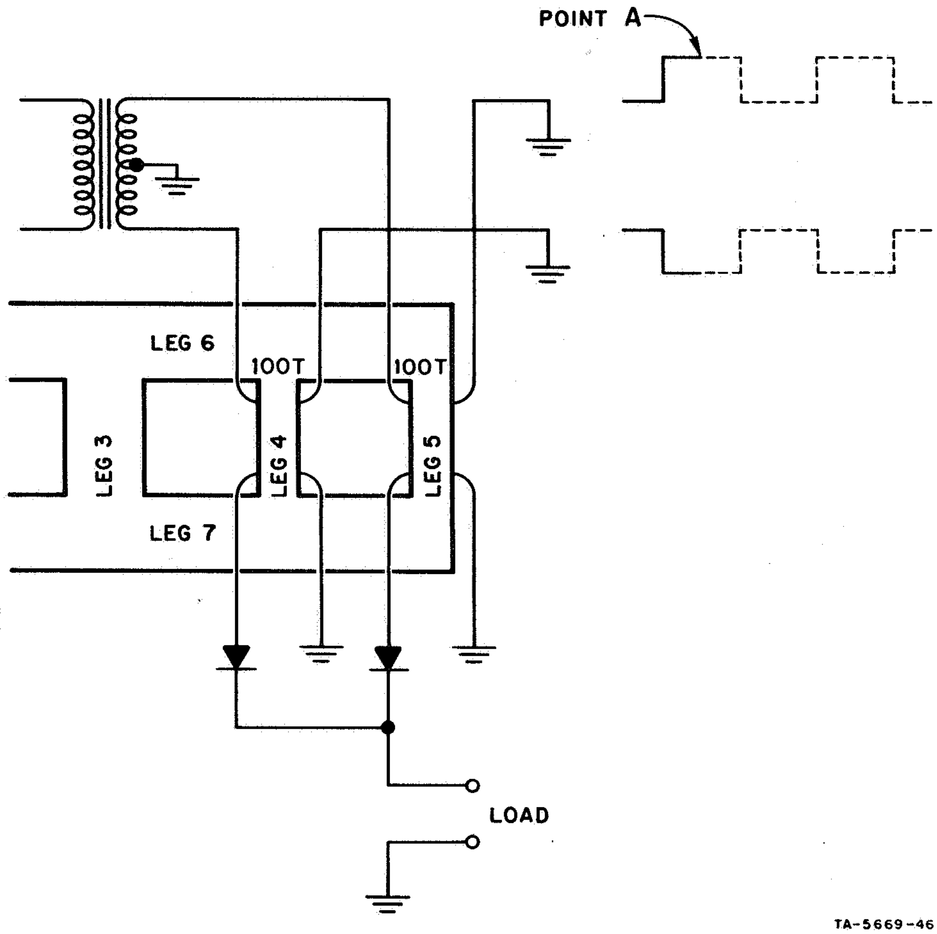

FIG. 7 COUPLING APERTURE

The increase of current in the primary of Leg 4 tends to equalize the effective voltage applied to the two legs by decreasing the effective voltage applied to Leg 4 due to the increased drop across the resistance of the Leg 4 winding and increasing that applied to Leg 5. The effective voltage on Leg 5 increases with increasing current in the primary of Leg 4; this is because it carries some of the secondary load on the secondary of Leg 5, thereby reducing the current in the primary of Leg 5. Ideally, the primary currents in Leg 4 and Leg 5 would become equal, in order to balance the rates of change of flux in the two legs. Two alternative ways to balance the flux change in the two legs are either to reduce the voltage applied to the primary with the unloaded secondary (Leg 4 in this case) to a level equal to the effective voltage applied to the loaded leg (Leg 5), or to increase the voltage applied to the primary of the loaded leg. These alternative approaches can be accomplished simultaneously by lowering the voltage applied to the ends of the two primary windings below ground by some appropriate amount. With this voltage set at zero, the currents in the two primaries are equal. As the magnitude of this negative voltage is increased, the current decreases in the Leg 4 primary (less drop in its windings is required) and increases in Leg 5. The sum of the primary currents stays constant while the voltage changes until the point is reached where the current in the Leg 5 primary passes through zero and reverses. Thereafter, the difference between the currents stays constant. The preceding explanation was made relative to the state of the drive voltage marked Point A on Fig. 7. The same arguments apply to the other half of the square wave, except that the effects on Legs 4 and 5 are reversed.

The reason for applying a voltage to the ends of the primary windings has to do with the effect on the control circuit. The MMF's resulting from currents in both the primaries and secondaries on the two legs interact with each other to produce a net MMF tending to switch flux in the rest of the core. This MMF is applied to Legs 6 and 7. If the net MMF is in a direction to switch flux counterclockwise through Legs 6, 3 and 7, Leg 3 will have to be held saturated upward with a bias MMF. Leg 3 must be saturated upward for proper operation of the switch. If the net MMF is clockwise, no bias is needed, because Leg 3 would stay saturated in the upward direction. The direction of the net MMF applied to the rest of the core as a result of the MMF's applied to Legs 4 and 5 depends upon which driving MMF is the larger, Leg 4 or Leg 5. The driving MMF on a given leg is its primary MMF minus its secondary MMF. If the driving MMF is greater on Leg 4 while it is in an upward direction, then the MMF applied to Legs 6, 3, and 7 is in a counterclockwise direction, and vice versa if the driving MMF on Leg 5 is greater in the downward direction. The <u>sum</u> of the two primary MMF's has two components: the MMF reflected from the secondary MMF, and that required to switch the flux in the two legs of the aperture. As explained above, a voltage applied to the ends of the primary windings changes the distribution of this total MMF between the two primary windings. Assume that this voltage has been adjusted to a level where the total primary MMF is provided by current in the Leg 5 primary winding (zero current in Leg 4 primary). Now the driving MMF is obviously greater in Leg 5 in the downward direction and the MMF on Legs 6, 3 and 7 will be in the clockwise direction. By the same reasoning, on the other half cycle of the driving square wave, the driving MMF will be greater on Leg 4 in the downward direction driving Legs 6, 3 and 7 in the same direction. In general, it is desirable to operate in this mode since no bias MMF is required to hold Leg 3 saturated in the upward direction. The MMF applied to the rest of the core increases as the voltage applied to the ends of the primary is increased. It would appear that the level could be increased to a point where the voter bias would no longer be necessary, since the voter bias applies a clockwise MMF through Legs 6, 3 and 7. The reason this technique cannot be used relates to the operation when the switch is in the off condition. In the off condition, there is no secondary current to disturb the original balance that exists between the two halves of the square wave. A voltage on the ends of the primary windings in the off case upsets the balance and large currents flow to restore the balance with voltage drop across the winding resistance. The voltage on the ends of the primary windings must be derived from the switching of the coupling aperture, so that it goes to zero when the switch is turned off. Since the voter bias MMF must be present when the switch is off, it cannot be derived from the primary winding bias voltage. The primary bias voltage can be generated from a special secondary on the coupling aperture of about two turns or by passing the load voltage through a low resistance. The circuit described in this report uses the later approach with the resistors having a value of 0.03 Ω. The circuit is shown in Fig. 7. Note that a separate resistance was used in series with each secondary winding. The experimentation carried on in the laboratory showed this configuration to be very stable under both normal and simulated failure modes of operation. The 0.03 Ω resistors do not provide enough bias voltage on the primaries to produce the condition where the net MMF applied to Legs 6, 3, and 7 is in the desired clockwise direction. The resistance required to produce this condition would be about three times as large. This much resistance would represent significant power loss. It was decided that the more practical approach was to use less resistance to save power and to accept the inconvenience of having to provide a source bias MMF.

It is suggested that more work could profitably done in the area of biasing the primary windings. There was not sufficient time to pursue the work further with the funds remaining. It is not clear just what the net power loss really is when all factors are taken into account. With the primary voltage bias set at the ideal level, power is lost in the power circuit but gained in the control windings. The voter MMF's are reduced and the source bias is eliminated. The optimum arrangement has not yet been determined.

V FAILURE MODES

The underlying reason for the tolerance of failure inherent in the magnetic switch is that the switching mechanism is magnetic flux reversal. Since the flux exists in a solid metal structure without joints, junctions, or connections, and since the only known types of flux reversal failure relate to temperature, radiation, or mechanical strain far beyond that which can be tolerated by semiconductor devices, failure of the basic switch mechanism (the core) can be ruled out as a reliability problem. If it can be shown that the flux can be switched to its off configuration regardless of failures in windings and other external circuitry, then the switch is fail safe (a safe failure is the condition in which the switch turns off automatically or in response to a signal). Relating the argument to the switch of Fig. 5, the switch is fail safe so long as the coupling aperture can be saturated downward under failure conditions. An additional reliability requirement is partly internal and partly external to the switch. The square-wave power source obviously must not be shorted out. In some circumstances, short-circuit conditions can be burned open; however, in this case, where shorted turns can occur in either the power source transformer or the blocking aperture winding, burn-open is impractical because conductors are relatively large. Attempts to burn the short open would be as likely to weld them more permanently as to burn them open. The recommended approach to the problem of shorted turns on the blocking aperture winding is to lay the winding on the core in uniform spirals so that a short could only occur between adjacent turns, producing only single-turn shorts. A single-turn short acts essentially as a loaded secondary. If the resistance of a single turn is not less than 0.01 Ω, the load current reflected to the source is only 0.5 A and the switch would remain off. The resistance might have to be maintained higher than 0.01 Ω to limit the heat generated by the current in the shorted turn. The resistance used would depend on a compromise based on

(1) Power drain caused by the shorted turns,

(2) Power loss due to the increase in resistance of the winding under normal conditions,

(3) Heat generated by current in the shorted turn, and

(4) Mechanical strength of the wire.

The mechanical strength of the wire might become important as the wire is reduced in size to give the required resistance per turn.

Another approach is to use a number of parallel connected windings, each winding having small enough wire so that a shorted turn would burn itself open and the switch would continue to operate with current flowing through the remaining windings. There is a higher probability of breakage with smaller wires, but the redundancy of the parallel windings would probably compensate adequately, and an open-circuit failure is a safe failure.

The switch is made tolerant of control-winding failures with the circuit shown in Fig. 8. The winding is driven with a voltage source with the additional requirement that no series resistance be added except under the special circumstances described in Sec. IV-D. With this drive arrangement, two compensating effects result from shorted windings. The number of turns reduces and the total resistance (as seen by the drive voltage) decreases. They change by the same factor since the resistance per turn is essentially constant. The decrease in resistance causes an increase in current which is proportional to the decrease in

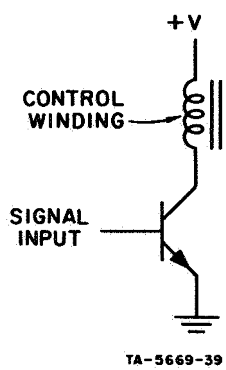

FIG. 8 DRIVER CIRCUIT

turns, resulting in the same MMF being applied to the core as before the short occurred. This discussion of short circuits applies to all three control winding (i.e., the voters, voter bias, and source bias).

The loading effect due to shorted turns on the control windings is of no significance, because the signals are dc. The switch changes position more slowly with shorted turns, but this is of no consequence in this application.

The open-circuit problem is not as simple as the short-circuit problem in the case of the control windings. There is no problem with the voter windings; an open failure is a safe failure. In the case of the source bias, open circuits can be protected against with redundant parallel windings, since there is no upper limit on the source bias level insofar as requirements for proper operation are concerned. The voter bias must be protected in a special way. Parallel windings cannot be used because there is both an upper and lower bound on the level of this bias. Parallel windings can be used if the windings are connected to each other every few turns. If a winding opens under these conditions, only a few turns are lost and the resulting small change in MMF can be tolerated. An open voter bias winding is less serious than other failures from the point of view that in order for a switch to be turned on erroneously because of an open voter bias winding, an erroneous voter signal must also be present. Means may be found by which the computer control unit can turn off its own erroneous voter signal.

The third and last area in which failures can occur is the coupling aperture, its windings, and the output circuitry. Open circuits are not a problem. The primary and secondary winding can be opened individually or in any combination with no undesirable results, except for a reduction of output voltage. The control circuit can turn the switch off in any case. The open failures in any combination are safe. The switch is inherently tolerant of short circuits in the coupling aperture area because the control circuits hold the switch on against counter MMF's generated by the load current. When short circuits occur in the primary, secondary, or between the two, the apparent increase in load current overpowers the control signals, partially or completely turning off the switch without the occurrance of harmfully large currents in any of the windings. The same result occurs when the load is shorted.

There should be no problem of windings shorting to the core if adequate insulation is provided between them; occurrence of a simple short will not affect operation. Multiple shorts in the coupling aperture are fail safe, but only a single short to the core can be tolerated at the blocking aperture or control winding section of the core.

A demonstration unit, shown in Fig. 9, was constructed to show the effect of simulated failures on the operation of the core. All of the windings and external circuit components are connected together with banana-plug jumpers. Extra windings of various numbers of turns are included for simulating various short-circuit conditions. This board is also convenient for connecting up the other types of circuits described in the next section.

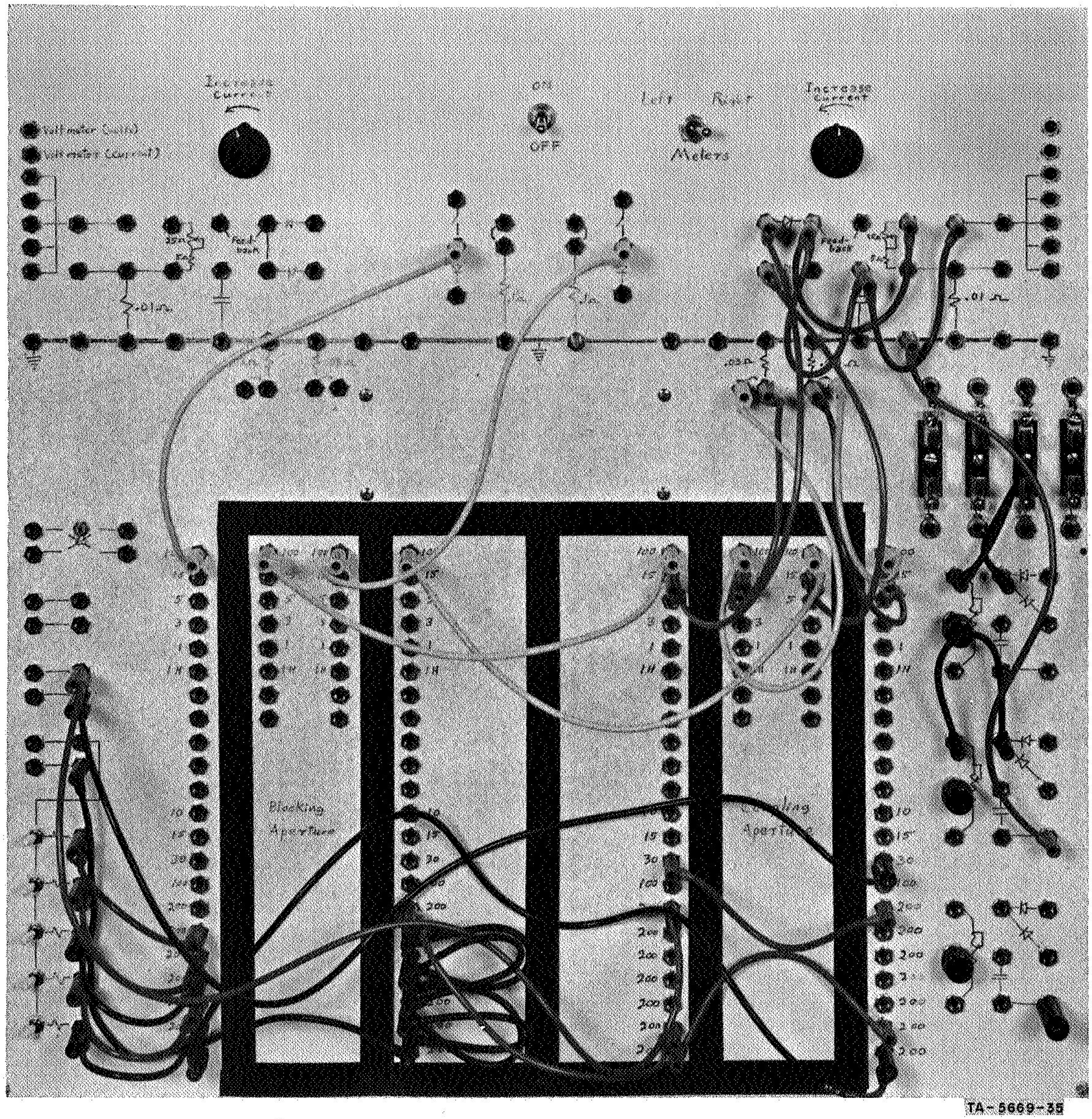

FIG. 9 FAILURE MODE DEMONSTRATION UNIT

VI PERIPHERAL INVESTIGATIONS

A. Snap-Action Switch

The snap-action switch is the same as the recommended version described in the report, except that feedback is connected from both the coupling and blocking apertures, this feedback is of sufficient magnitude to hold the switch in either position once it has been driven there. The feedback from the coupling aperture is the same as for the normal switch, except for more turns in the feedback winding. A secondary winding must be added to the blocking aperture to provide the feedback current for the off position, as shown in Fig. 10.

The snap-action switch can be driven on or off with pulses, either position being stable. Voting inputs can be provided in essentially the same way as for the dc-controlled switch. The experimentation with this configuration indicated that the switching pulse required must have an MMF-time area of approximately 1.5 ampereturn-milliseconds. (This value should not be treated as a specification because it is affected by the amount of feedback used.)

Two set inputs are needed, since no way has been discovered to provide for a single reversing input.

B. Continuous Structure and Series Configuration

The series-switch configuration is an alternative to the recommended one where only one redundant unit of a group is to be turned on at a time. Some thought has been given to this configuration, although the final decision was to allow for more than one redundant unit to be turned on at a time.

There are no blocking apertures in the series configuration. The coupling apertures of the switches are connected in series in the same manner as the blocking and coupling aperture in the recommended switch. A switch of this type would only need one aperture plus a flux closure path. The part of the switch to the right of the broken line A in Fig. 10 represents one possible configuration of a series type switch.

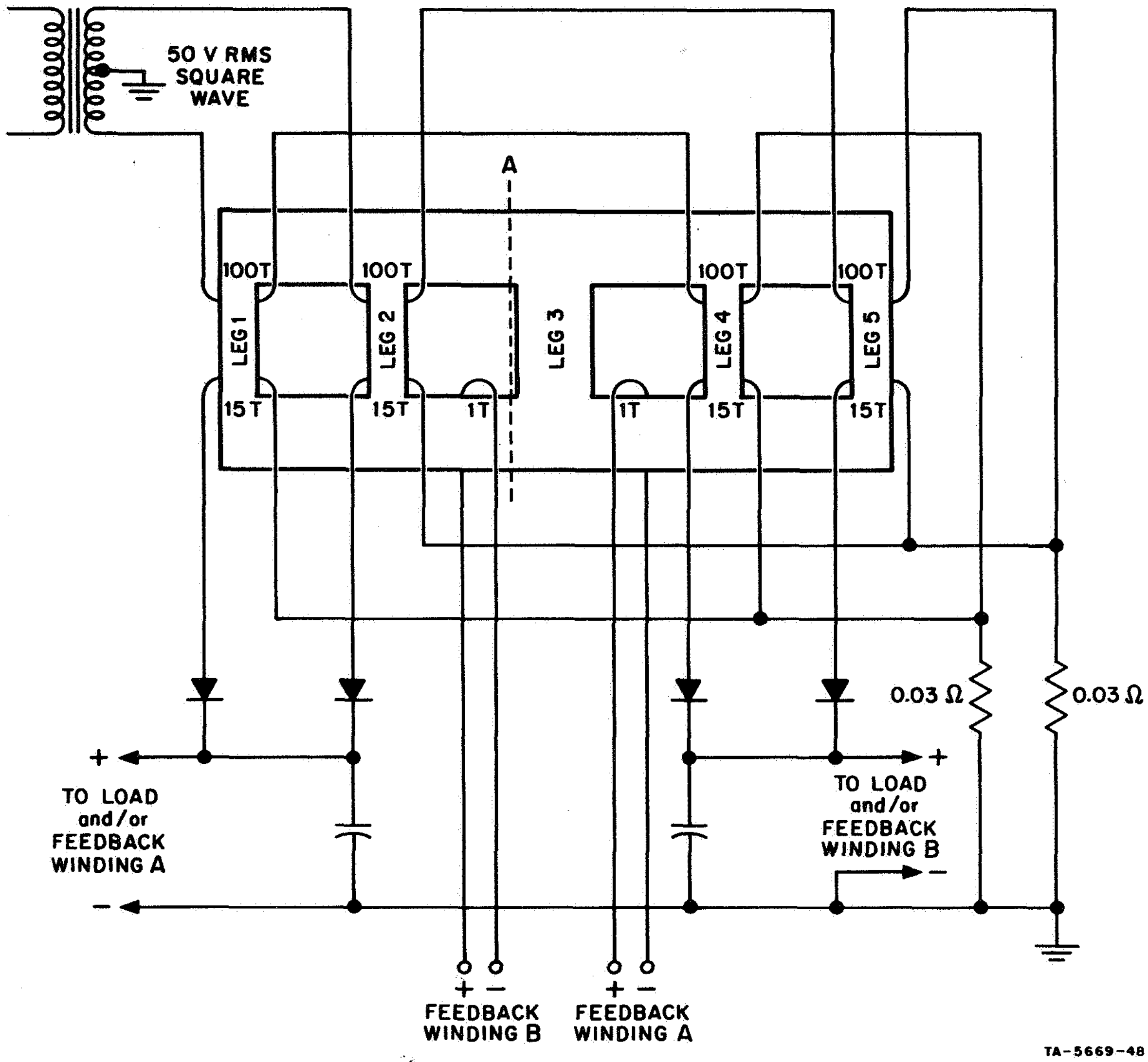

FIG. 10 DUAL COUPLING-APERTURE CIRCUIT

Two series type switches can be incorporated into the core of Fig. 10 by adding a secondary winding and rectifiers to the blocking aperture making it identical to the coupling aperture. With this configuration, there are two power switches in one core, one and only one of which is on at all times. This technique indicates the method that can be used to combine multiple series-type switches into one continuous structure. The idea can be extended to more than two switches per structure by extending the horizontal legs of the core and adding vertical legs to provide more apertures. The source leg in the middle and the horizontal legs must be increased in cross section to provide for an adequate flux closure path for the number of apertures involved.

C. Transistor/Rectifier Circuit

In a low-voltage power circuit the power lost in the rectifiers is significant. This loss can be reduced to some extent by using transistors instead of diodes, since there is less voltage across a saturated transistor. A transistor/rectifier circuit was breadboarded and used as a rectifier circuit for the switch as shown in Fig. 11. This circuit is not recommended because the added complication reduces the reliability of the circuit.

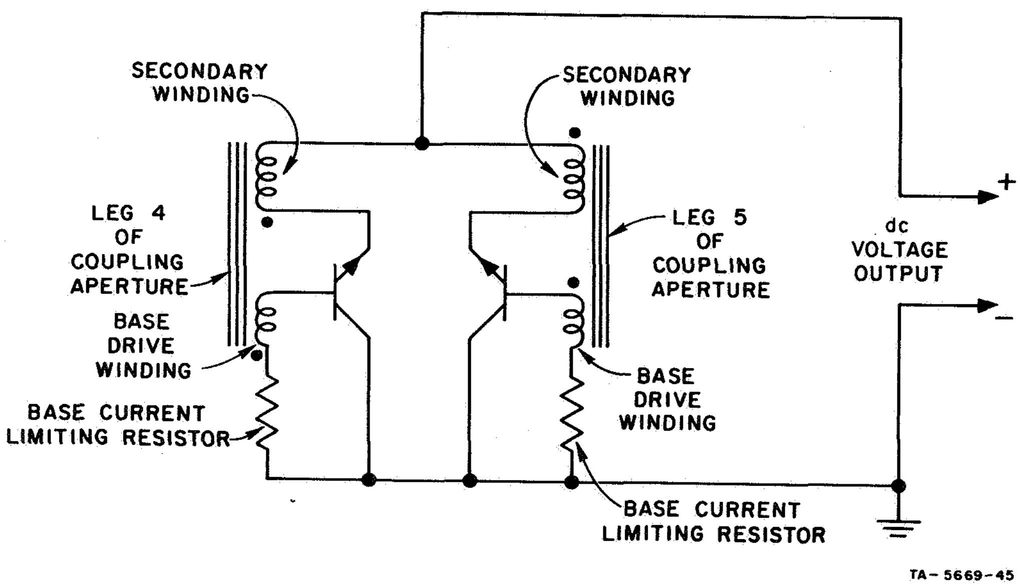

FIG. 11 TRANSISTOR RECTIFIER CIRCUIT

D. Diode-Primary Circuit

Introducing diodes in series with the primary windings eliminates the need for the balancing resistors in the recommended circuits. This approach was not recommended because in the event of failure of these diodes, dangerously high currents occurred and the switch could not be considered fail safe.

E. Magnetic Amplifiers

The use of magnetic amplifiers in this switching application was considered early in the program. They were not recommended because no way was found to provide the fail-safe characteristics required of the switch.

F. Power Source Frequency

The weight and volume of the switch can be reduced if the power source frequency is increased. The cross-sectional area of all the core legs or the number of turns in the primary and secondary windings change in inverse proportion to the power source frequency.

The maximum practical frequency is limited mainly by the recovery time of the rectifiers and by leakage inductance. When the square wave driving voltage reverses polarity, the conducting rectifier maintains conduction in the reverse direction until the stored charge is cleared out. The transition is further delayed by the leakage inductance, which slows the falling of current in the primary and secondary on one leg of the aperture and the building up of current in those on the other leg. This transistion time is independent of the frequency of the square wave. As the frequency increases the transistion time becomes a larger proportion of the total period. Under present conditions the transistion period is approximately 20 percent of a half period of the square wave. Increasing the frequency by a factor of two would make the transistion period 40 percent of a half period. It is estimated that any significant increase in frequency beyond this factor would begin to cause serious deterioration in performance. The above estimate of allowable increase in frequency would allow a decrease in the weight of the switch by about a factor of two.

VII POWER DRIVER

The power driver is not meant to be a practical driver circuit from the point of view of cost or good design. It was built to provide an adequate input for three switches for as small a time and money expenditure as possible.

A square wave is generated by a stable free-running multivibrator type circuit. This circuit drives a voltage-power amplifier circuit that is coupled to the switches with a transformer. The circuit diagram for the driver is shown in Fig. 12. The odd value resistors in the generator circuit resulted from adjustment of the amplitude and balance of the waveform. The oscilloscope trigger circuit is provided with two clip-lead connections for triggering each whole or half cycle.

The power supplies are connected with strip line to reduce inductive transients. The input to the final stage of the amplifier is also connected with strip line for the same reason.

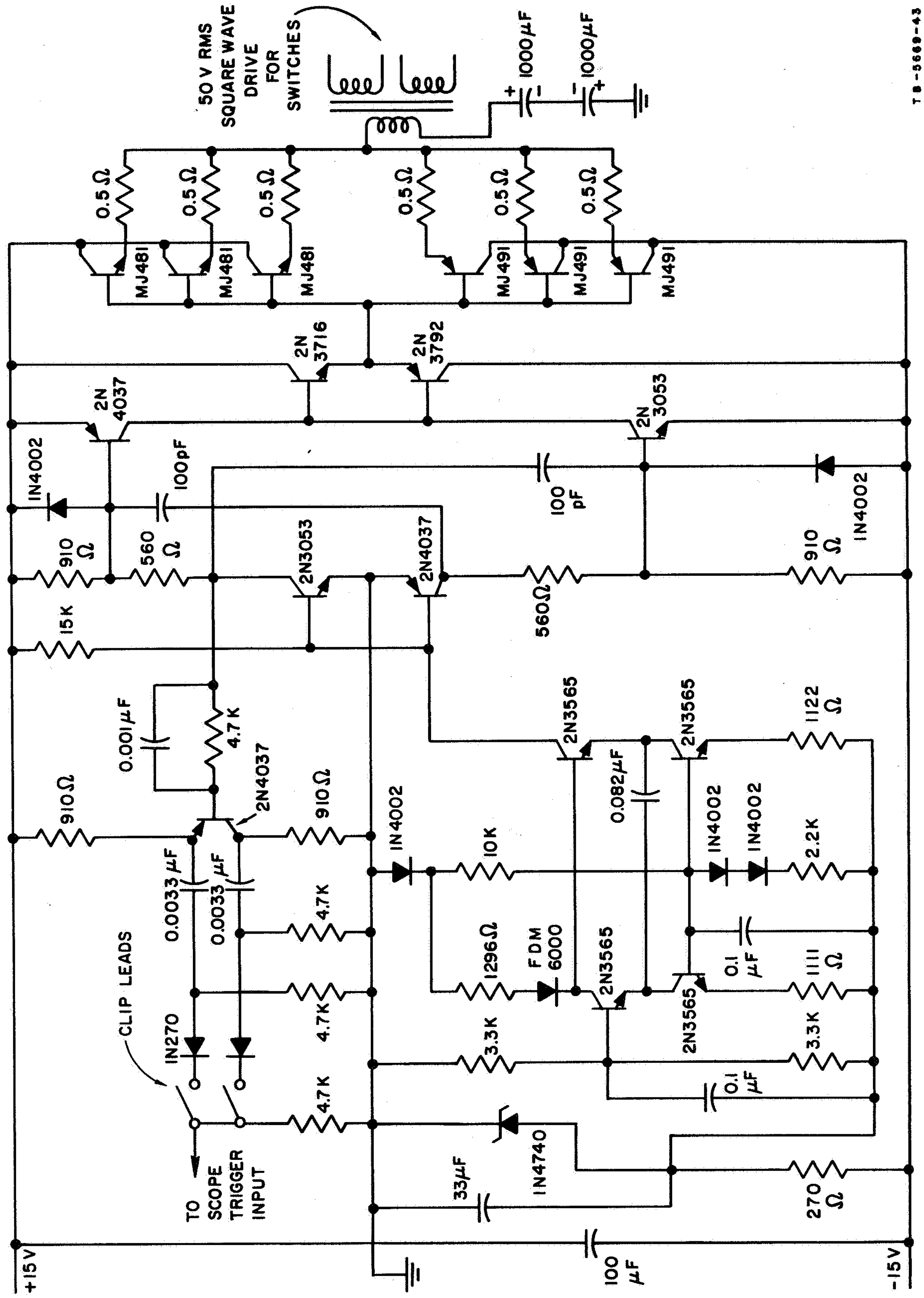

FIG. 12 POWER DRIVER CIRCUIT

Appendix A

CORE-WINDING CALCULATIONS

The size and shape of the aperture between Legs 4 and 5 of the core in Fig. 6 is the main problem to solve in designing the core for minimum volume. Early in the project, a computer program was written to calculate the crucial dimensions of an experimental core shape related to the series connected type switch of Sec. VI-B. While this shape is not the same as that of the present parallel connected type, it was possible to make the necessary extrapolations to obtain dimensions for the present core that came close to the minimum volume values.

Two trade-offs can be made relative to the size and shape of the aperture to obtain minimum volume for the core plus its windings. The area of the aperture can be decreased, providing the cross sectional are of the core is increased to compensate. The area of the aperture determines the number of primary turns which can be used. For a given number of primary turns, the cross-sectional area of the core is calculated to give the required volt-microsecond capacity, as explained in Sec. IV-B-2. Since the volume of the core varies inversely and the volume of the winding varies directly with the area of the aperture, the minimum volume of the core and winding together is the point where the volume of the winding equals the volume of the core. This fact is easily seen by comparing the volume lost in the core with the volume gained in the winding for a small increase away from the optimum. Not only is the percentage change equal between the two, as the volt-microsecond capacity requires, but the actual amount of change in volume of the two is equal. With any pair of values of core and winding volume, where the two areas are not equal, the equal percentage change would not give an equal volume change, giving a net decrease in the overall volume.

A simple geometric calculation shows that the volume of the windings is 162 times (dimension $\chi)^3$. This indicates a near optimum balance between the area of the aperture and the cross-sectional area of the core. The other trade-off, which must be adjusted for minimum volume, is the volume of magnetic material in the vertical and horizontal legs. Since their cross-sectional areas are related by a factor of two, only their relative lengths can be changed. The relative lengths can be changed by changing the length and width of the aperture, keeping the area the same. Here again, the minimum volume exists where the net volume of all of the vertical legs equals the volume of the horizontal legs. In the recommended shape, the aperture is square. This shape does not give equal volume in the vertical and horizontal legs. The horizontal legs have four times the volume of the vertical legs. The vertical legs would have to be extended and the horizontal ones shortened considerably to achieve minimum volume. It turns out, however, that the minimum volume shape, which requires the aperture to be twice as high as it is wide, reduces the volume of the core by 20 percent and the overall volume by 10 percent. It was felt that the convenience in winding and increased structural strength of the square aperture more than compensated for the 10 percent reduction in volume resulting from the elongated aperture.

The discussion has related to one aperture and one winding, but it applies to the whole core and all of the windings, since there is, in effect, a winding in each aperture.

Appendix B

DIRECTIONS FOR WINDING CORES

1. INTRODUCTION

These directions relate to the four-aperture cores purchased by JPL from Magnetics Incorporated. Any discrepancies between these instructions and those implied by the Design Section in the main body of the report are due to the fact that it is assumed that these cores are to be wound and used in a laboratory environment.

The directions for winding the core are based on a compromise between maximum power switching capacity versus ease of winding. Number 24 AWG wire is recommended for the primary. This wire size allows ample room for the required number of turns without having to lay the windings in neat spirals for high packing density. If there is difficulty in getting the required number of turns through the apertures, smaller wire may be used at some sacrifice in maximum power. It is recommended that a thermocouple be mounted under the primary winding of the first core so that the maximum power can be determined in terms of temperature limits on the particular insulation used.

Since core thickness has been found to vary significantly, due to variation in the number of laminations, the number of primary turns will have to vary correspondingly, as explained later.

2. PREPARATION OF CORE

Before preparation of the core, measure its thickness. The number of primary and secondary turns will vary slightly from core to core on the basis of this information.

The core is quite rugged, but it should be kept in mind that the magnetic material is strain sensitive.

Glue a half-round plastic cover on the top and bottom of each cross leg, as shown in Fig. B-1. RTV Silastic is excellent for this purpose. Glue 0.25-inch thick fiberboard bars on both top and bottom

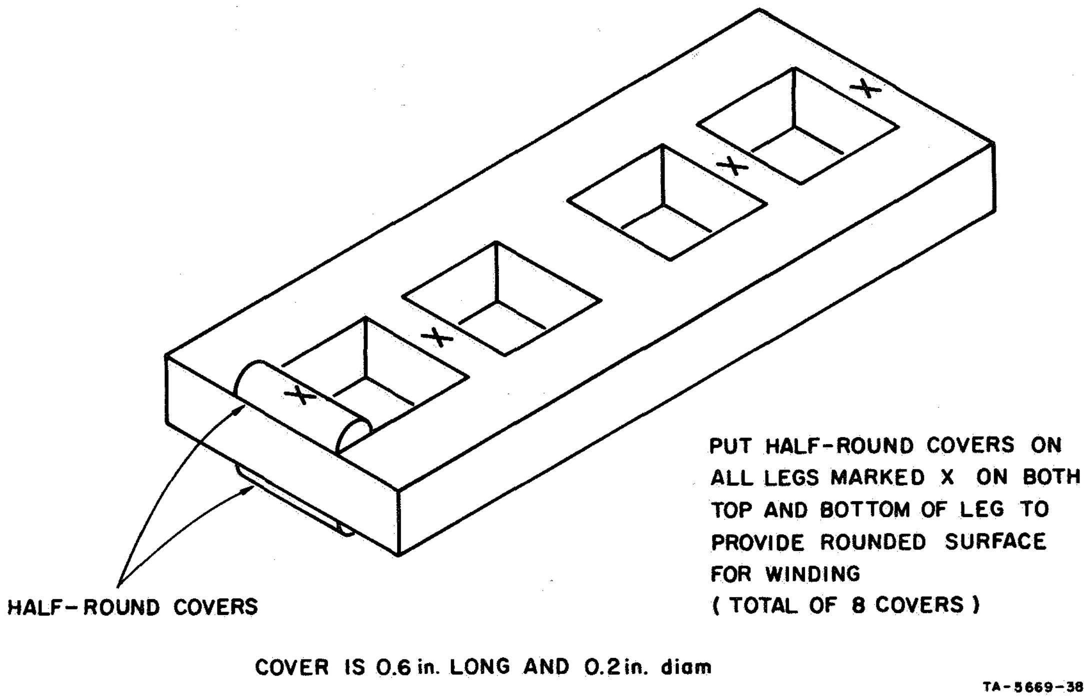

FIG. B-1 HALF-ROUND COVERS

of the two lateral legs of the core, as shown in Fig. B-2. Align the edge of the bars carefully with the <u>inside</u> edges of the lateral legs. Let the bars protrude 0.75-inch out from the ends of the core for mounting purposes.

Fill the cracks between the ends of the half-round leg covers and the sides of the lateral-leg bars with glue, so that windings will not pull into these cracks.

A piece of tape around each cross leg and its covers is a worthwhile precaution against shorting windings to the core.

3. WINDINGS

a. Primary

Size 24 wire is reasonable for the primary winding, considering the general level of power involved, the aperture sizes, and the number of turns to be put through the apertures. Wire size may be reduced if there is difficulty getting all the turns through the apertures.

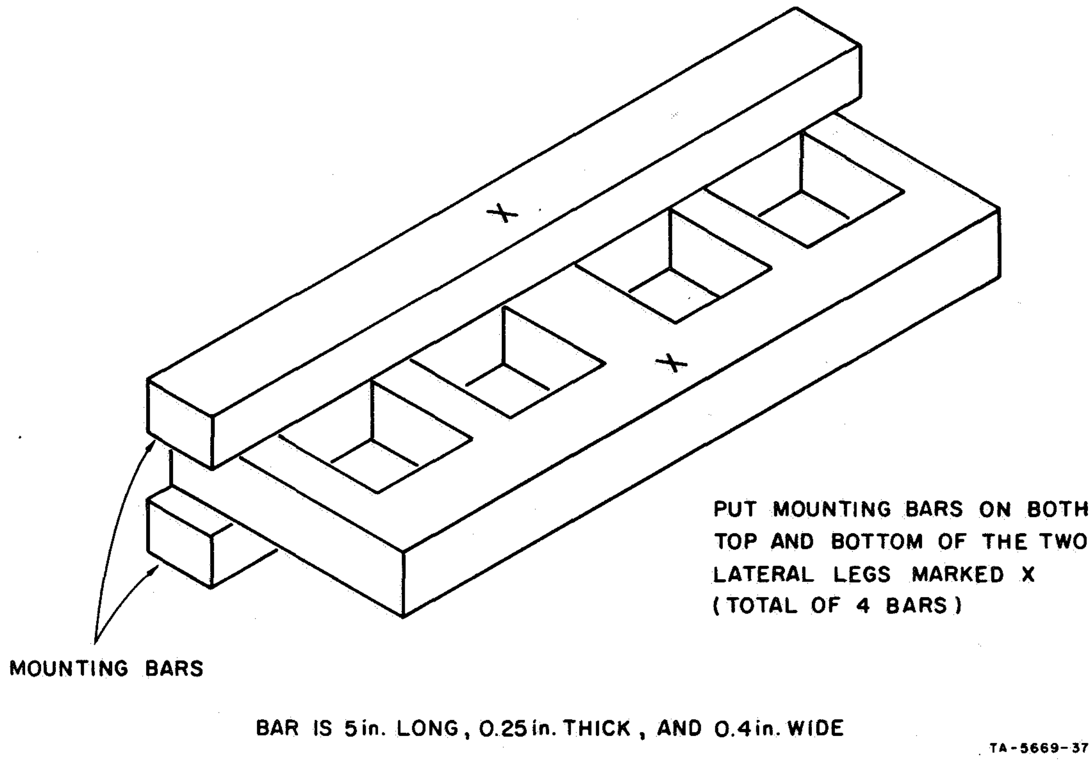

FIG. B-2 MOUNTING BARS

The number of turns is 100 altered by the thickness according to the following equation:

$$\text{Number of turns} = \frac{0.430 \text{ inch}}{\text{thickness}} \times 100 \quad .$$

Nyleeze is recommended for under 20 watts because of its convenience in stripping and resistance to abrasion and cracking. For more than 20 watts, ML is recommended, because of its ability to stand high temperature.

b. Secondary

Size 18 wire is recommended for the secondary winding. The turns are calculated from the following equation:

$$\text{Turns} = \text{Primary turns} \times 0.15 \quad .$$

The secondary is wound on the outside of the primary for ease in altering the output voltage in the event that higher voltage is needed to accommodate more filtering and/or regulation.

The insulation should be the same as that on the primary winding.

c. Primary - Secondary Tests

At this point, the windings should be tested for primary secondary shorts and core-winding shorts. It is recommended that the insulation between the primary and secondary be tested to stand off at least 200 V.

The volt-microsecond capacity of the primary should also be tested. Apply a current to the secondary winding to hold both legs of the coupling aperture saturated downward. Apply the square wave source to the blocking aperture. Increase the positive supply voltage on the square wave source, noting any tendency of the core to saturate. Saturation is easiest to detect by watching the current peak up violently toward the end of each half cycle when saturation is reached. Saturation should not occur below 55 V rms at the input to the blocking aperture. If it does, the core has an abnormally low saturation flux level and the number of primary turns must be increased to compensate. If the primary turns must be increased, the secondary turns must also be increased to maintain the 100:15 ratio. Although the number of primary turns may vary a turn or two from the calculated value, it is necessary that the number of turns on the two legs of any given aperture be exactly equal to each other, in order to have the required flux balance. Their equality can be checked if desired by switching the aperture back and forth with a temporary winding of a few turns, while monitoring the voltage on the primary windings. The primary windings on the two legs should be hooked up series bucking. It is easiest to detect a difference in turns by integrating the bucking signal with a simple resistor-capacitor integrator and with a heavy short around the lateral leg leading to the aperture. Removing or adding a turn will give a calibration for the magnitude of difference signal to look for when there is a difference in turns.

d. Control Windings

i. Bobbins

It is strongly recommended that bobbins for the control windings be ordered from professional bobbin makers, rather than handmade in the laboratory. The whole bobbin can be ordered and then it can be cut in two and glued around the core. Figure B-3 shows the recommended bobbin dimensions.

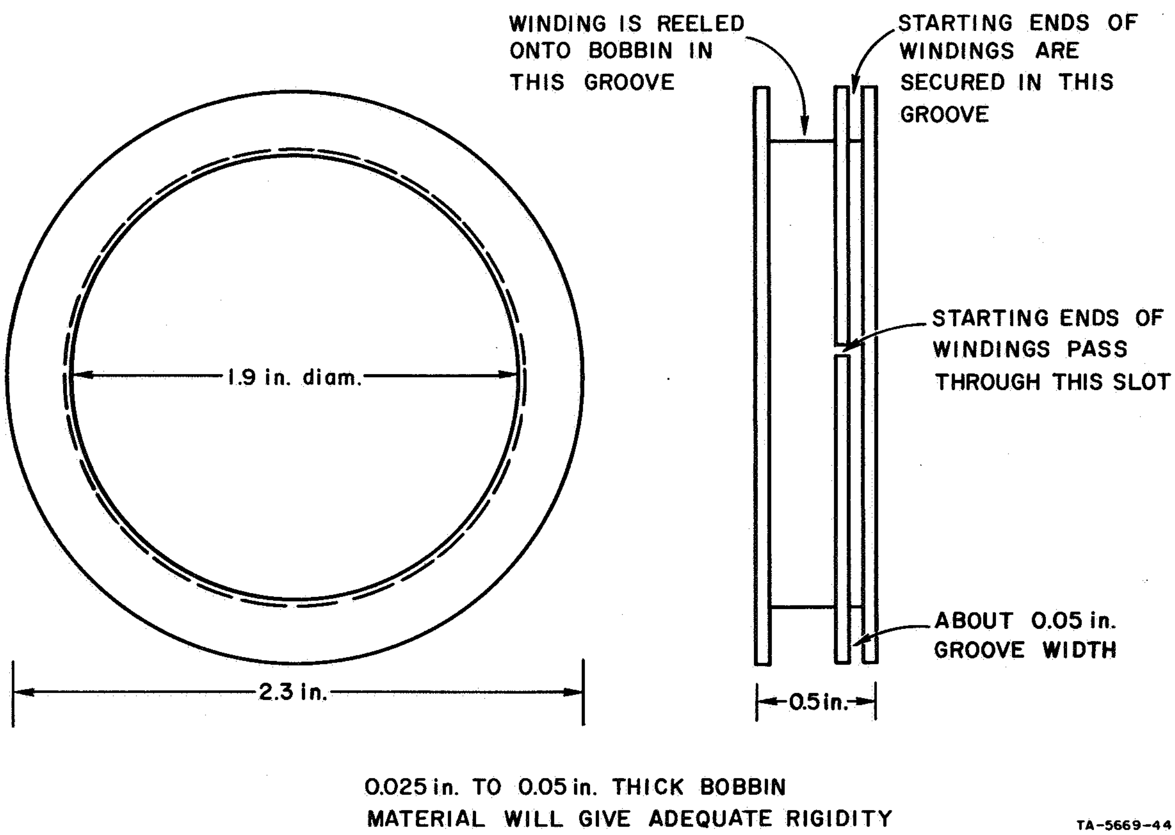

FIG. B-3 CONTROL WINDING BOBBIN

ii. Wire

Number 36 wire is recommended for the voter and voter bias windings. Number 34 wire is recommended for the source bias winding. Nyleeze insulation is recommended.

iii. Winding Process

Seven 200-turn windings are required on the bobbin around the blocking aperture and three 200-turn windings on the bobbin around the coupling aperture. All of the windings on a given bobbin are wound at the same time, reeling the windings on the bobbins as shown in Fig. B-4. The starting ends of the windings are secured with tape or by other means in the narrow groove between the two closely spaced flanges on the bobbin. Provide about 6-inches of wire in this

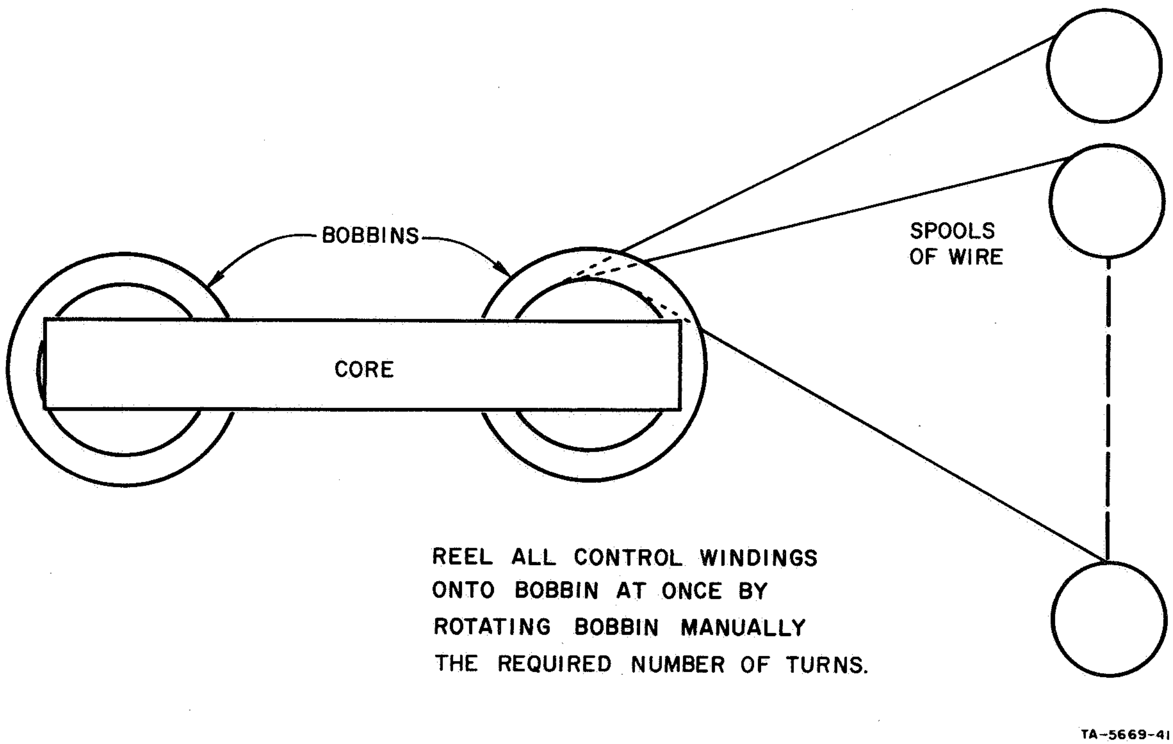

FIG. B-4 WINDING TECHNIQUE

groove for terminating to solder pins after the winding process is completed. After the ends of the wires are secured, pass the wires through a slot in the inner flange into the main body of the bobbin for winding. Reel the wire onto the bobbin from all seven spools of wire at the same time, counting the turns of the bobbin to obtain the required number of turns on the winding. The reel is easily handled manually and the time required to put a set of windings on is not excessive. When the winding is completed, it is helpful to secure the winding with tape before cutting and soldering the ends of the wires to terminals. The starting ends of the windings can now be taken out of the narrow groove and soldered to terminals. The bobbin should be held securely to the core mounting bars with glue or other means after the turns are reeled on. Another possibility is to break the bobbin out from under the windings. This allows the windings to be taped down close to the core, but makes it messy for any later alterations of the windings.

4. CIRCUIT FOR THE SWITCH

The circuit drawing showing the connections of the power windings to the input square wave and the load, is shown in Fig. 3. Be careful to connect the polarities correctly.

The circuit for the control windings is shown in Fig. B-5. The resistors in series with the voter windings are provided under the assumption that the windings will be driven with approximately 5 V and that the resistance of each winding will be approximately 50 Ω. The resulting 9 ampere-turns MMF per voter is the basic requirement in selecting number of turns, wire size, and series resistor. These three parameters can be altered as desired to reduce turns or get rid of the resistor as desired so long as the 9 ampere-turns MMF is preserved and the drive is a voltage rather than a current source. The relationship that must be satisfied is

$$\frac{VT}{R} = 9 \quad ,$$

where

V is the driving voltage,

T is the number of turns, and

R is the resistance of the winding plus the series resistor.

The initial value of the voter bias MMF before the adjustment is made is 12 ampere-turns. Here again the turns, wire size, and series

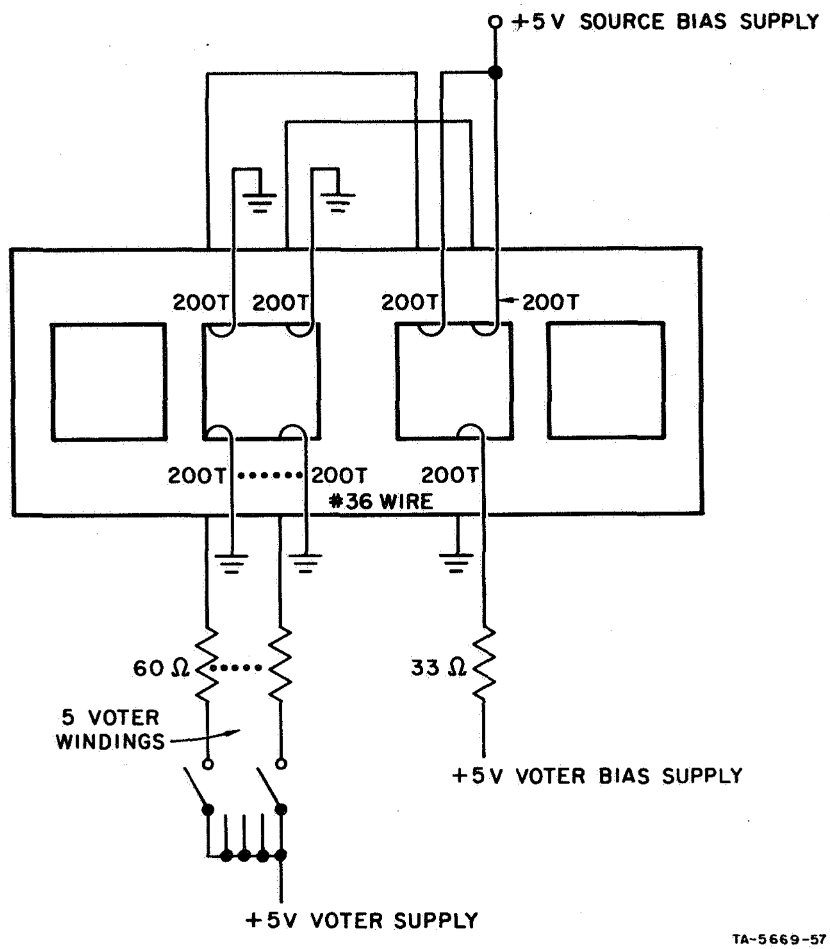

FIG. B-5 CONTROL WINDING CIRCUITS

resistance may be altered, so long as the required MMF is maintained according to the expression:

$$\frac{VT}{R} = 12 \quad .$$

The source bias winding is designed to apply approximately 28 ampere-turns in the downward direction on the coupling and blocking apertures. Number 34 wire is recommended. Assuming 5 V drive, the connection indicated in the drawing would provide about 32 ampere-turns bias without any series resistor. This value gives plenty of safety factor. It is important that the windings are connected as shown in the diagram so that the MMF's exactly counteract each other producing a bias on the source leg only.

The value of the resistance in series with the voter bias winding should be adjusted to compensate for core variation or small errors in numbers of turns on control windings so that maximum variation in temperature and load can be tolerated. The adjustment is made in the following way:

Hook the circuit up in normal fashion using the resistance values given in the diagram and the load intended for the switch. Correct the one turn of feedback as shown in Fig. 5. Decrease the resistance until the point is reached where two voter inputs will just barely turn the switch on. This is the minimum allowable value of the resistance. Next increase the resistance to the point where, with two voter inputs active and the switch on, the turning off of one of the voters will just barely turn off the switch. This is the maximum allowable value of resistance. Use a value of the resistance half way between the maximum and minimum values. Although determined at room temperature, this value will track well over the temperature range and over a reasonable variation in load. If the resistor has the same temperature coefficient as the winding, tracking will be better.

The drawings for the three breadboard switches delivered to JPL appear as Appendix C.

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Appendix C

DIAGRAMS OF THE SWITCHES

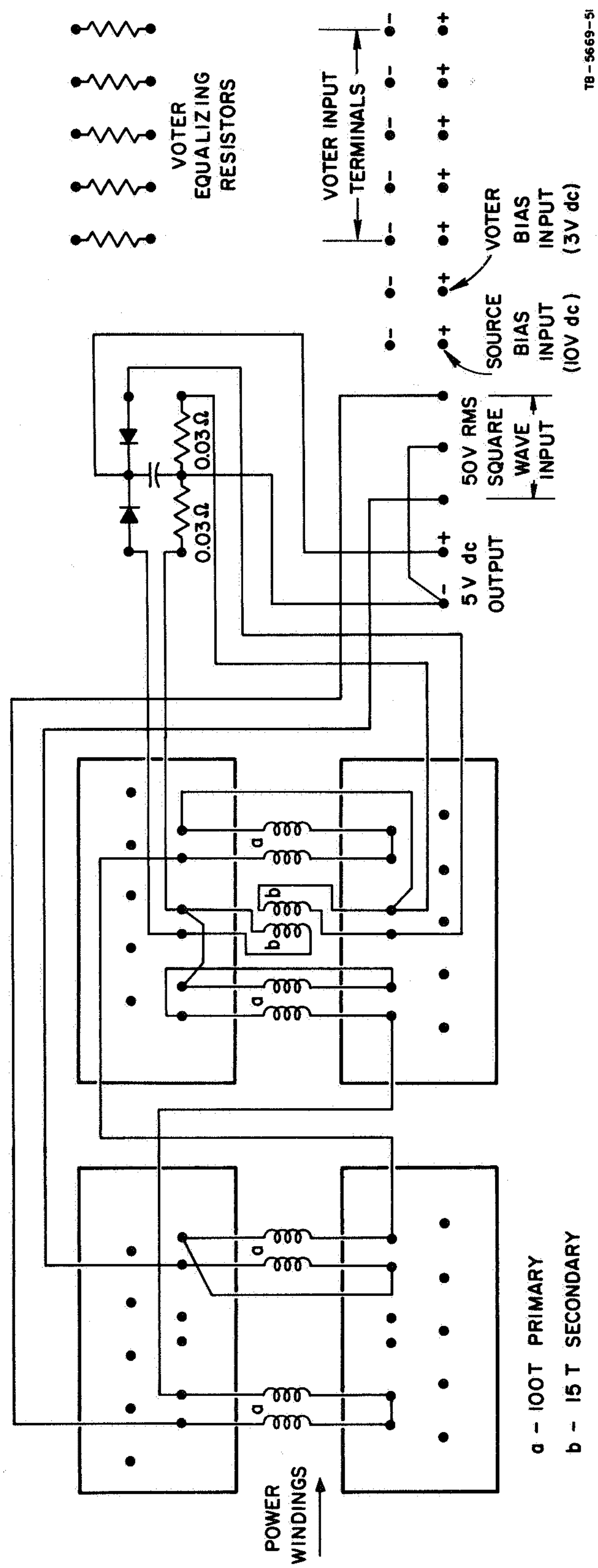

FIG. C-1 CORE NO. 1 POWER CIRCUIT

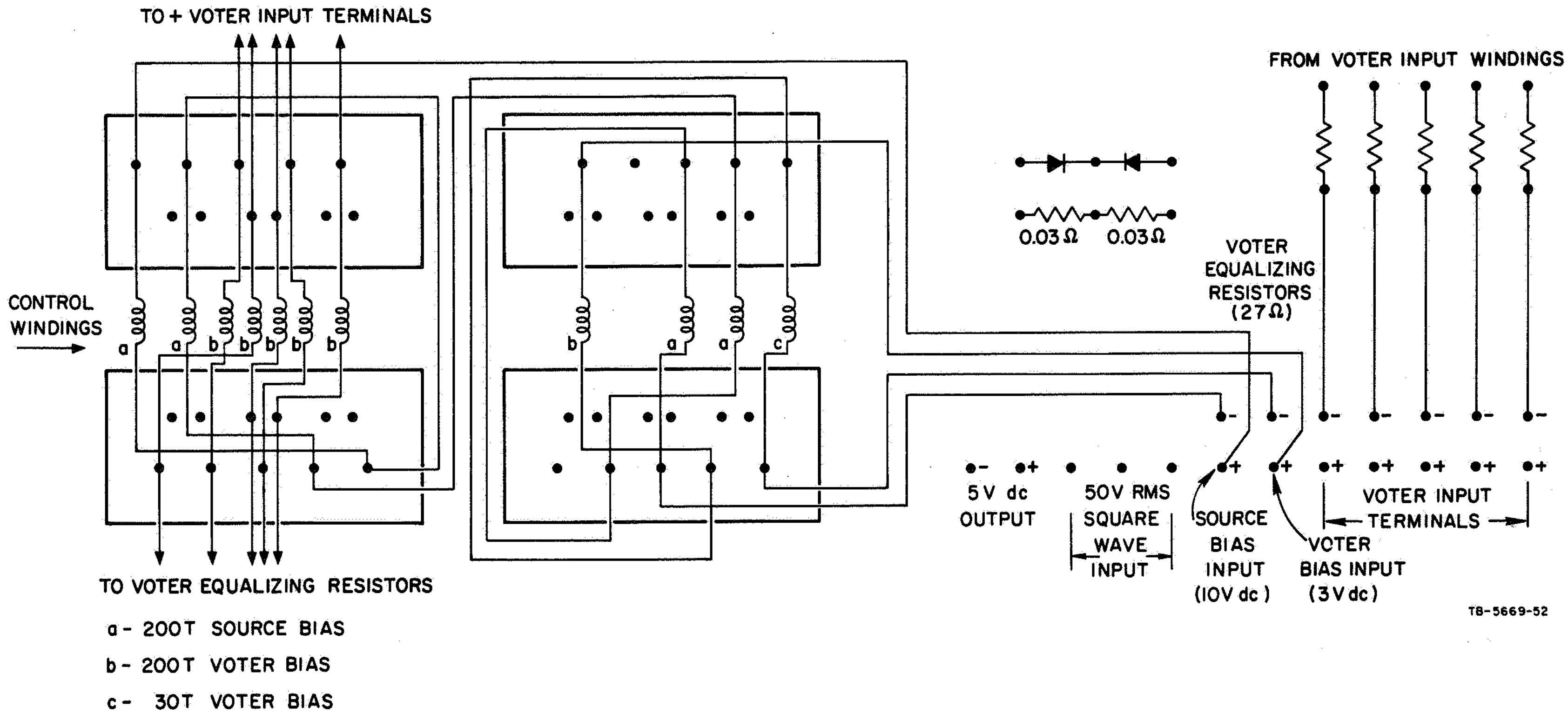

FIG. C-2 CORE NO. 1 CONTROL CIRCUIT

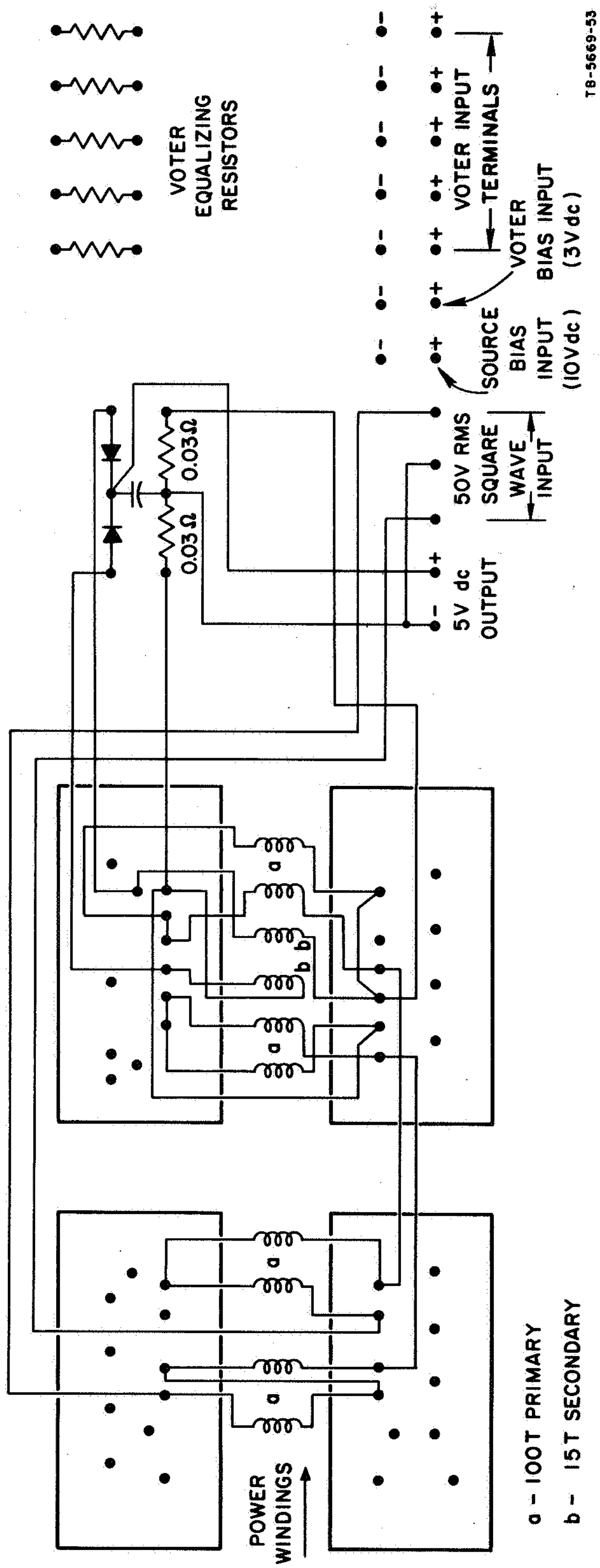

FIG. C-3 CORE NO. 2 POWER CIRCUIT

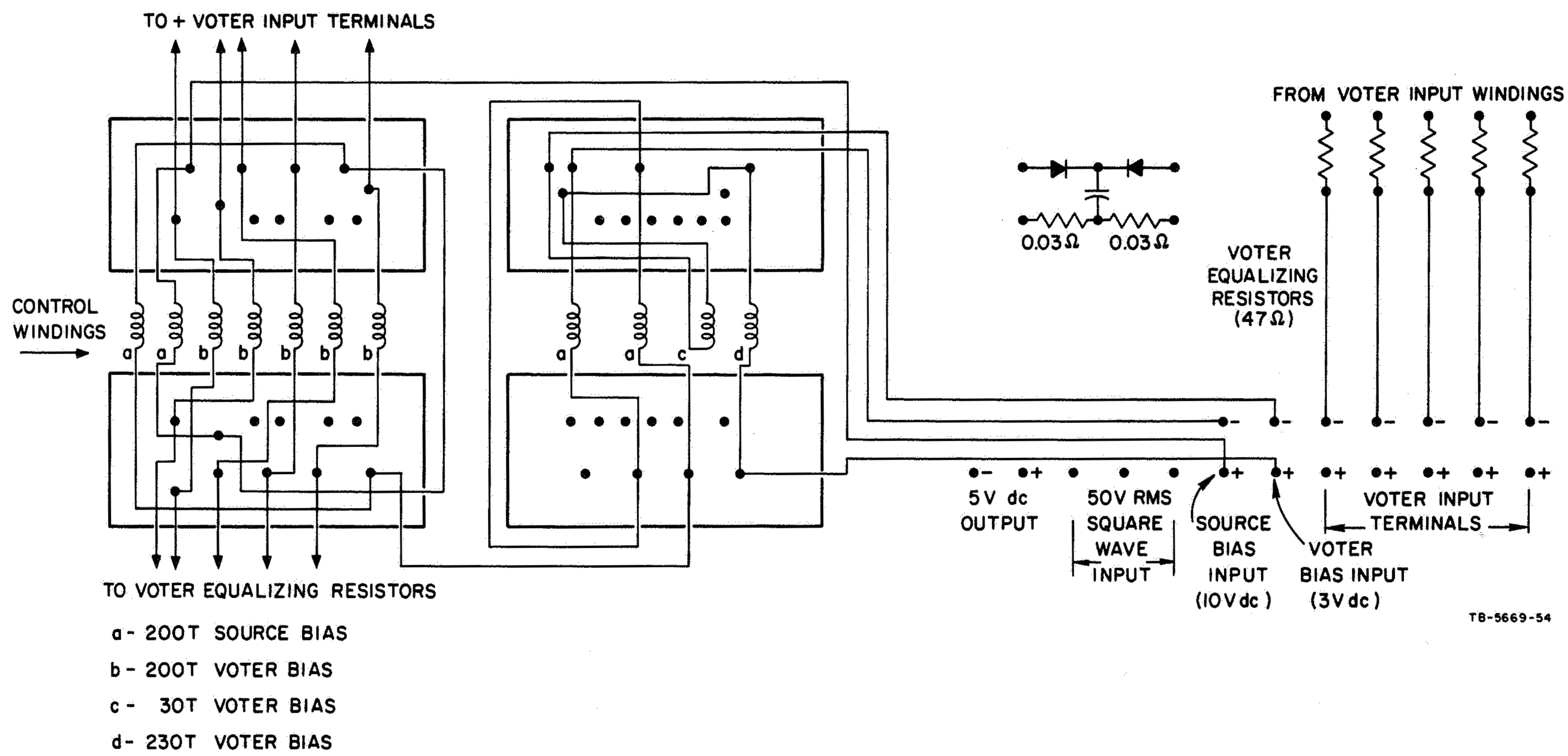

FIG. C-4 CORE NO. 2 CONTROL CIRCUIT

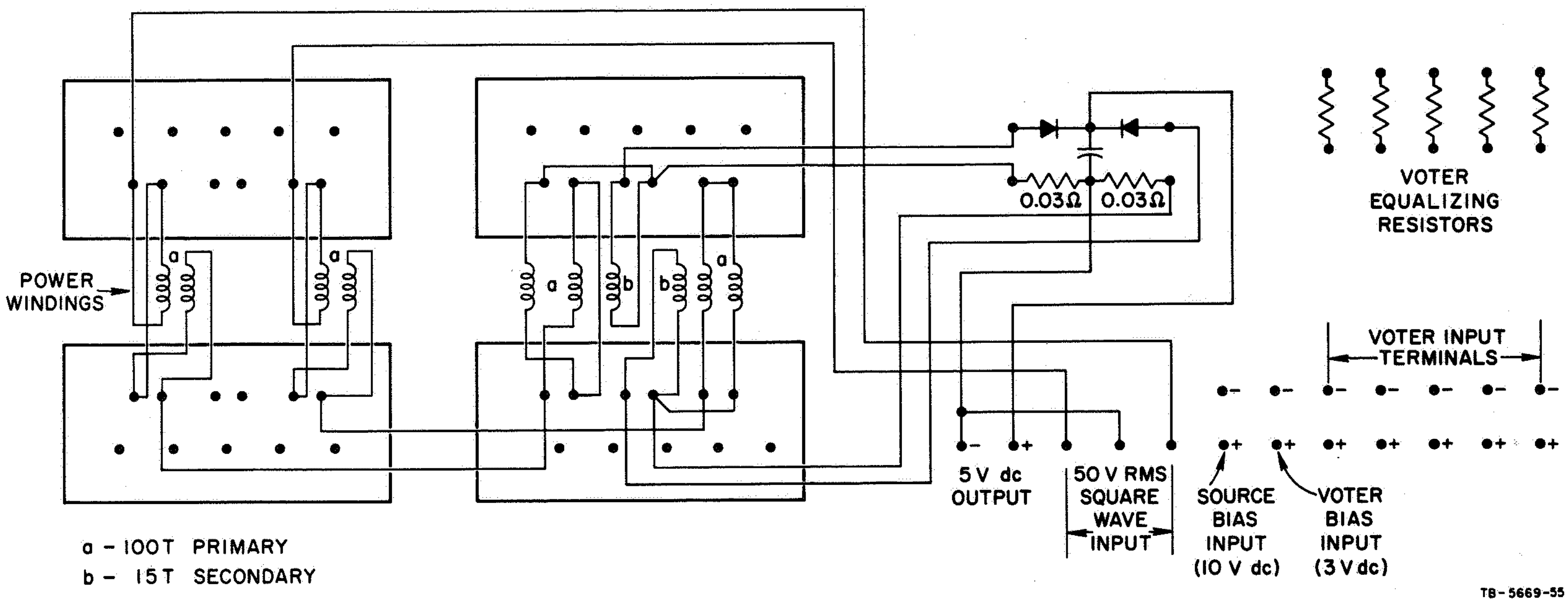

FIG. C-5 CORE NO. 3 POWER CIRCUIT

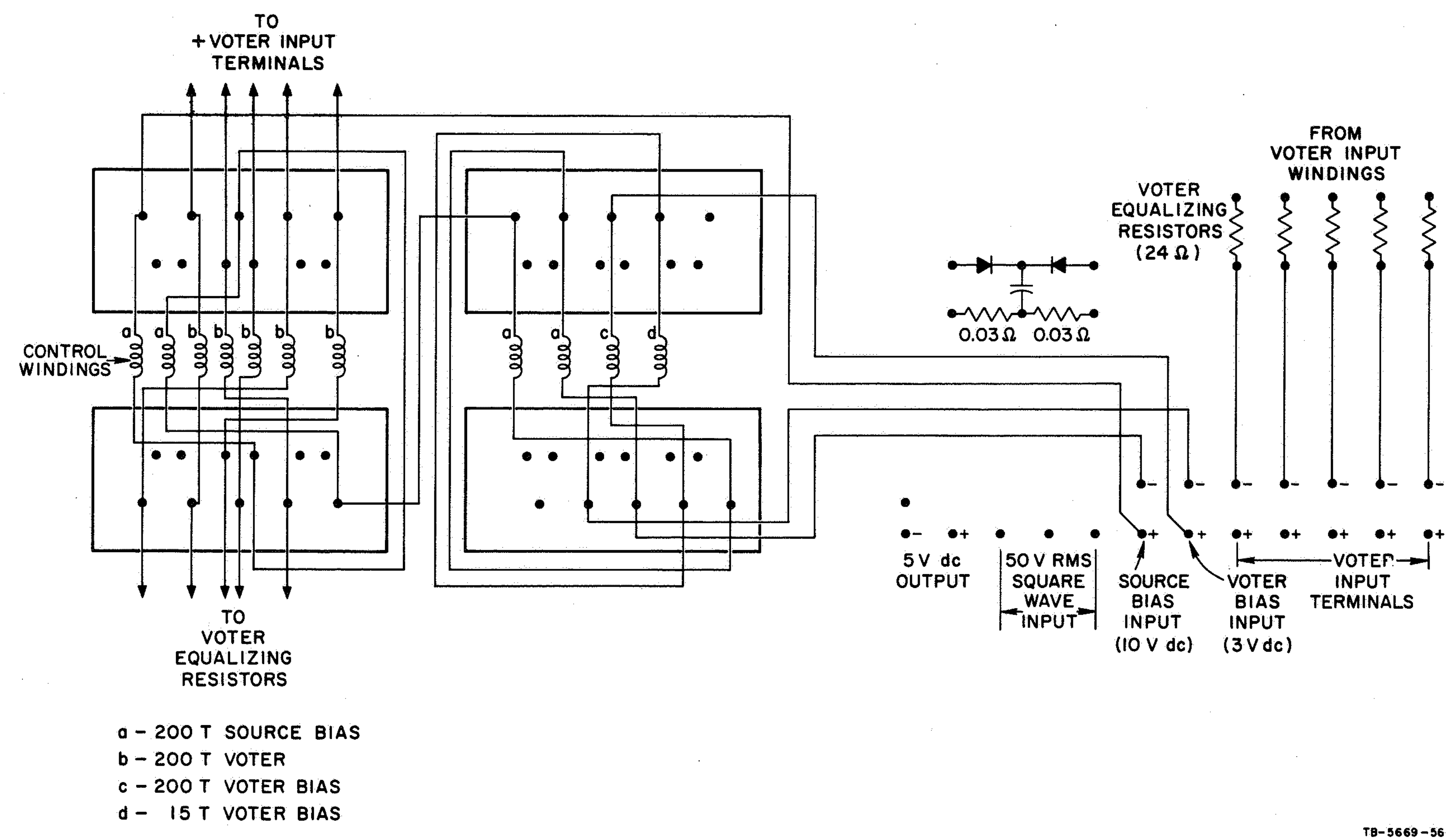

FIG. C-6 CORE NO. 3 CONTROL CIRCUIT

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